Factorial Techniques applied in Chemical Plant Cost Estimation: A Comparative Study based on Literature and Cases

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Abstract

Economic aspects are a major player in assessing design alternatives for chemical plants. The study focusses on capital cost estimation by factorial techniques originating from the early works of Lang and Hand. A literature study is conducted on consecutively developed techniques, these are categorised and compared among others on the basis of appliance strategies, cost item inclusions and statistical backing. Similarities were observed: It was found that methods are especially proximate in estimating off-site costs and indirect costs, and systematically lack statistical analyses. The latter may be overcome in future methods with the help of cost estimation software. Quantifiable results were obtained from case study experiments with six factorial techniques applied to twelve cases. The chance that a technique successfully estimated the actual construction value, measured with reference values, appeared to be more dependent on case type than factorial method type; the database behind the method had a larger influence than factors applied.

Keywords: Capital cost, chemical plants, factorial techniques, comparative study

Preface

This report is a partial fulfilment of the final outcome of the Master Thesis project course of the Chemical Engineering program at Delft University of Technology.

I would like to make acknowledgements to the following persons who have been supporting my work and been comforting my stay at TU Delft. First I thank professor dr. ir. André de Haan for providing me the possibility and the means for this project. During the execution of the project he was always available for guidance or advice.

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Lastly I thank my family and in particular my girlfriend Suzanne Galjaard. Her support, patience and care during this graduation journey kept me moving forward. Together we look ahead to new challenges and a bright future.

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Contents

Chapter 1

Introduction

Cost estimation is a vital part of each construction project, chemical plants are no exception. Strategic decisions made by company management whether to approve or hold a construction project revolve around the counterbalance of operational expenditure (OpEx) and capital expenditure (CapEx) predictors. This thesis focusses on capital cost estimation for chemical plants, in particular factorial techniques, which are widely applied by chemical engineers to scan and assess feasibility of design alternatives. Because decision making requires accuracy levels dependent on the project maturation status, the claimed and actual observed accuracy of such methods are especially interesting.

The field of factorial cost estimation finds it's origin in the post-World War II economic expansion in the United States of America. The journal *Chemical Engineering* fulfilled a central role as the dominant platform promoting the development of factorial techniques. The editors of *Chemical Engineering*, Chilton[1] and Matley[2], have actively contributed by compiling all relevant articles on cost estimation in 1960 and 1979 respectively. Consequently these works contained the state of the art at that time period.

After that period the addition and diversification of methods has increased both the size and complexity of the cost estimation scientific field. Published methods, now mainly in books, pursued the qualification of being the best, most accurate method. Little effort however is contributed to survey, inspect, organise, compare and scrutinise the methods already available in literature. The thesis work in front of you is a result of the ambition to fill that gap. The goal is to not merely compare the available techniques via literature and cases, but also to pinpoint improvement strategies.

The goal is achieved in three steps: First general cost estimation facets for chemical plants are introduced in chapter 2. Then in chapter 3, factorial cost estimation techniques are organised according to chronology, type and defining characteristics. General comparisons are made based on application strategies, inclusion of cost items, accuracy claims, statistical background and more. General trends, weaknesses and rooms for improvement are discussed in a qualitative way including opportunities to include cost estimation software as a step forward. The final chapter 4 employs case studies to compare six selected techniques in a quantifiable manner.

Chapter 2

General Theory of Cost Estimation

This chapter contains a general introduction into capital cost estimation theory applied in chemical plant building projects. The aspects of project development and the part cost estimation plays in that perspective are discussed in the first part. Then general but vital questions are answered such as: What parts of a plant are included in an estimate? And what types of estimation techniques are out there? The chapter ends with a short discussion on equipment databases and time correction indices.

The goal of this section is to make the reader familiar with all the aspects in cost estimation that are especially concerned with factorial techniques (chapter 2.3), the topic of this study. Excellent relatively recent introductions into the topic are also provided by Dysert[3] or Ulrich and Vasudevan[4]. However, those literature sources are less extensive than this text or differently focussed.

2.1 The Estimator's Goal

The goal of an estimator is simple: Produce the most accurate estimate possible with the means made available. The 'means' in this sense is expressed in time or monetary budget. A closer look is given to the relationship between estimate accuracy and preparation effort.

2.1.1 Estimation Classes & Accuracy

The planning of a construction projects starts at the origin of an idea to the engineering phase to the end of the actual physical construction. According to Rödl, Prinzing and Aichert a project may be divided into three phases[5]. The division is motivated by the fact that management decisions are taken after the first two phases, which require the preparation of different CapEx estimate documents. The phases are as follows.

1. **Conception:** Determine the basic ideas without performing much engineering work, except constructing provisional equipment lists flow diagrams for multiple alternatives.
2. **Definition:** Generally one alternative is taken to the next phase, detailed engineering is performed on this case.
3. **Execution:** The construction project's execution is continuously monitored.

As the project definition level increases the availability of information applicable for cost estimation also increases, therefore a more accurate estimate is expected as the project matures. Note that it is often not worthwhile to spend a large amount of effort at the start of a project to increase the accuracy of an estimate, for much of the project scope may still be changed. Also decision making often does not require high levels of accuracy at the initial phases.

The general trade-off between preparation effort and expected accuracy is clearly visible in table 2.1, published by AACE International[6]. In this table estimate classes are defined, with class 5 being the most rough estimate and class 1 being the most definitive. Estimates in class 3, 4 and 5 are prepared in the conceptual phase to compare alternatives. Documents containing class 1, 2 and 3 estimates are filed in the definition stage for execution approval. The notes [a] and [b] in the table provide ball park numbers for the expected accuracy and preparation effort. The focus of this thesis work is on factorial methods, which are stochastic of nature and are categorised as a class 3 or 4 estimate. The actual accuracy of these methods is discussion of debate and differs per method and may shift over time. Couper[7] published a reasonable number, namely that factorial methods should be within -25% to +30% accuracy.

Table 2.1: The five capital cost estimate classes and the characteristics as defined by AACE International, reproduced with permission[6].

ESTIMATE CLASS	MATURITY LEVEL OF PROJECT DEFINITION Expressed as % of complete definition	END USAGE Typical Purpose of Estimate	METHODOLOGY Typical estimating method	EXPECTED ACCURACY Typical +/- range relative to index of 1 (i.e. Class 1 estimate) [a]	PREPARATION EFFORT Typical degree of effort relative to lease cost index of 1 [b]
Class 5	0% to 2%	Screening or feasibility	Stochastic (factors and/or models) or judgement	4 to 20	1
Class 4	1% to 15%	Concept study or feasibility	Primarily stochastic	3 to 12	2 to 4
Class 3	10% to 40%	Budget authorisation or control	Mixed but primarily stochastic	2 to 6	3 to 10
Class 2	30% to 75%	Control or bid/tender	Primarily deterministic	1 to 3	5 to 20
Class 1	65% to 100%	Check estimate or bid/tender	Deterministic	1	10 to 100

[a] If the range index value of "1" represents +10/-5%, then an index value of 10 represents +100/-50%.
[b] If the cost index value of "1" represents 0.005% of project costs, then an index value of 100 represents 0.5%.

2.1.2 The Costs of an Estimate

The cost of making an estimate is closely linked to the preparation effort since it mainly consists of engineering salaries. Table 2.2 shows the approximate costs associated to estimating, the data in the table is merged from Pikulik and Diaz[8], Humphreys and English[10] and Sila[11]. The costs of making an estimate is a function of targeted accuracy and project size. Minimum engineering requirements for small plants, while larger plants often install more expensive pieces of equipment that do not necessarily increase engineering work. One should not aim for a higher accuracy than necessary at a particular stage in project development for time and money spend on estimates may increase rapidly while accuracy gain may be low.

Table 2.2: Projected costs of performing a CapEx estimate. The values are given as % ranges of the total project cost on a 2017 basis (chapter 2.4.2), based on references [8],[10] and [11].

	Project Dollar Value		
Accuracy Range	$ 1,500,000	$ 15,000,000	$ 30,000,000
-30% to + 50%	0.2 - 0.4	0.05 - 0.2	0.02 - 0.05
-15% to + 30%	1 - 2	0.3 - 1	0.1 - 0.3
-5% to + 15%	2 - 6	1 - 2	0.2 - 1

It is noted that the accuracy reported across literature is ambiguous. It was observed by the author of this work that reported accuracy varies substantially between methods in literature, while the methods employed were comparable in structure. The information displayed in table 2.2 should be used with caution.

2.2 Cost Categories

When it comes to estimating CapEx for plants it is useful to categorise costs, for preventing confusing and also improving overview for both cost reduction and discussion. If cost distributions are known it is easier to identify design alternatives. Although not every estimating technique requires full definition of cost categories, factorial techniques mostly do need some degree of categorisation.

Table 2.3: Generally accepted cost categories as determined by reference [14].

Direct Costs	*All costs related to the physical part of the plant*
1. Purchased equipment	Equipment costs including spare parts, equipment allowance, freight, taxes, insurance and duties.
2. Equipment Installation	Installation of purchased equipment including labour and materials for structural supports, insulation and paint.
3. Instrumentation & Control	The purchase, installation and calibration of instruments.
4. Piping	All the process piping including installation and insulation.
5. Electrical installations	Electrical equipment such as motors, conduits, grounding lighting, etc. Includes installation.
6. Buildings	Process buildings such as substructures, platforms and supports. Auxiliary buildings such as fire stations, administration offices, cafeteria and maintenance shops including elevators, lightning telephones etc.
7. Yard improvements	Site development for example site clearing, roads, walkways, parking area's, wharves etc.
8. Service facilities	Distribution and installations to provide for steam, power, compressed air and such utilities. But it also includes equipment used in for example the laboratory and office.
9. Land	Property cost, surveys and fees.
Indirect Costs	*All costs related to non-physical parts of the plant*
1. Engineering & Supervision	Administrative, process, design, cost engineering, procuring, consultant fees, travel etc.
2. Construction expenses	Temporary expenses during construction such as tools and temporary offices and roads. Also included is supervision, accounting, benefits, gaurds, permits, field tests, taxes, insurance and more.
3. Contractor's fee	Extra fees paid to account for contractors' work.
4. Contingency	An amount of capital reserved for unexpected issues or changes of scope.

No universal categorisation exists in literature, however general trends are visible. Aries and Newton[12] were in 1955 one of the first to publish a list of categories comparable to contemporary ideas. Peters [13] adapted it slightly a few years later. The collaboration of Peters with Timmerhaus[14] delivered a very complete categorisation that may be used as a checklist. An abbreviated version is shown in table 2.3, the full version is included as appendix A. Other good checklists are published in the books of Gerrard[15] or Baasel[16]. In many cases other authors merge direct costs, for example land and yard improvements are taken together. Or categories are split-up, an example would be to split the labour and material component for each subcategory. Or to estimate taxes, freight and duties or structural supports, insulation and paint are separately. Therefore the list is not shown to fix the categorisation, but is open for change. However it does give a good idea on the amount of parameters included in an estimate.

Auxiliary costs generaly not included in the estimate and not shown in the example table are cost for royalties, start-up expenses and working capital which may add up to a significant proportion of the total costs. Most complete estimation methods estimate the total depreciable costs (TDC), which also excludes land. More on this subject is available for reading in chapter 3.4.

2.2.1 What is Included?

As mentioned before the list shown in table 2.3 is not universal, factorial methods discussed in chapter 3 will generally not have the same cost categorisation. It is therefore essential that an estimator knows what is included in the estimate and whether this corresponds with the estimator's goals.

A building project may be located at an isolated site, called green-field or grass-root plant, then every aspect needs to be estimated. Whenever building is done in a brown-field, an integrated complex, an estimator might need for example to scale down the estimates for yard improvements or facilities as clearly explained by Seider et al[17]. An addition to existing plants may rule out other sections of the estimate as well. For example an addition may be done solely to the process part of the plant eliminating the need to estimate services and other geographical sections.

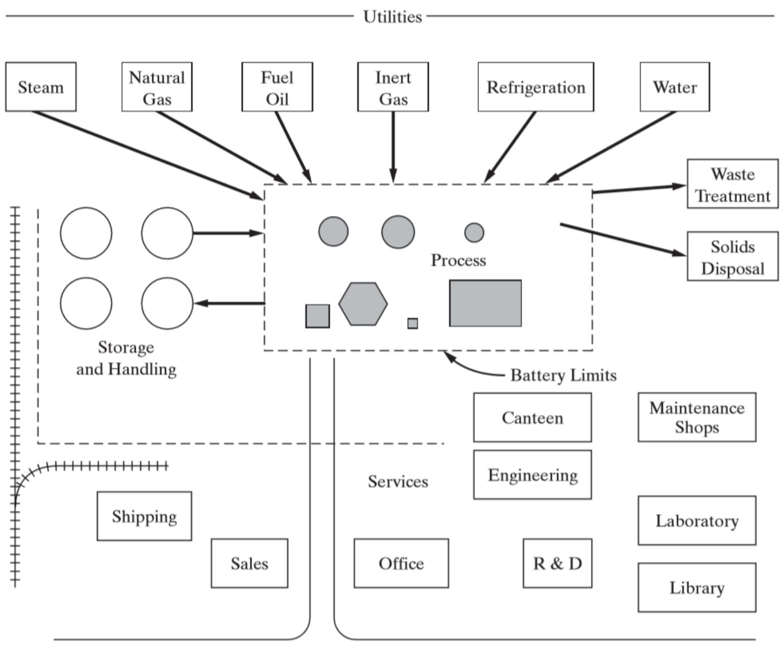

Figure 2.1: Schematic overview of geographical locations within a chemical plant put into sections, copied from reference [17].

The division of the plant in sections makes it easier to select estimation needs for addition projects. Often four categories are distinguished as shown in figure 2.1, made by Miller but published in the book of Seider et al[17]. Especially the term 'Battery Limits' is popular in estimating literature, but the estimator should watch carefully what is included in the term for that particular estimation technique for it is not always universal.

2.3 Types of Estimation Techniques

Multiple estimation technique types are to be found in literature. Although factorial estimation techniques are the focus of this study, others are briefly introduced in this section. Each technique may be associated with an accuracy and class as shown above in table 2.1. The list of techniques presented below are based on the work of Aries and Newton[12], Peters[13], Bauman[18] and Perry and Green[19] (2008 version). The first two cited books date back to the 1950's and 1960's, however the methods' basis remains unchanged. The following list is ordered from order of magnitude methods (class 5) to detailed methods (class 1 or 2).

- **Turnover ratio's**
  The total investment for a plant may be approximated by the turnover ratio, which link capital investment to sales in a linear relationship. Lists of ratio's have have been published per product for example by Kiddoo[20], however the data is often outdated.

- **The exponential method**
  The sixth-tenths rule of Williams[21] used for equipment pieces was proven to also be applicable on whole plant costs by Chilton[22], whose formula is shown in equation 2.1. It relates the known costs and capacity of plant A to the estimated costs for plant B at an intended capacity.
  $$Cost_{\text{B}} = Cost_{\text{A}} \cdot \left(\frac{Capacity_{\text{B}}}{Capacity_{\text{A}}}\right)^n \tag{2.1}$$
  The value of exponent n is product specific and published in literature for over 600 plant types by Remer and Chai[23].

- **Parametric models**
  Parametric models estimate the total capital investment based on a single formula correlating the major design parameters. This type of estimate has approximately the same category of accuracy as the factorial techniques. Therefore it is explained in more detail in the next section, chapter 2.3.1.

- **Factorial methods**
  These methods are the focus of this study. Basic flow sheets are prepared and equipment is sized. The equipment pieces are priced and specialised factors are used to account for the rest of the costs associated with construction. The subdivision of factorial methods and an in depth discussion is provided in chapter 3.

- **Detailed estimates** In the factorial methods, factors account for all costs other than equipment costs. In the definitive estimates every detail is costed separately based on flow sheets, plot plans, other detailed documents and labour hours. It is a large workload, but when the project is defined appropriately, it is the most accurate. It is often prepared for cost control during construction. Both the publications of Blecker and Smithson[24] and Navarrete and Cole[25] explain such methods in great detail.

2.3.1 Parametric Models

The parametric or functional unit method has some similarities with factorial methods and is therefore briefly discussed in this section. The origin of parametric models may be traced back to Hill[26] in 1956. His method was developed for low-pressure petrochemical industry and claimed an accuracy of 40% compared to detailed estimates. Nowadays it is believed the method produces errors from -50% to +100%. A successive method was developed by Zevnik and Buchanan[27] in the 1960's, which has served as a basis for later popular publications such as: Stallworthy[28], Wilson[29], Allen and Page[30], Taylor[31], Viola[32], Ward[33] and Klumpar, Brown and Fromme[34]. All these methods may be summarised in a single defining formula shown in equation 2.2, in which C is the capital cost, K a constant, N the number of functional units and F factors to account for a variety of parameters such as pressure, temperature or complexity. These factors are determined by supporting auxiliary equations.

$$C = K \cdot N \cdot F \tag{2.2}$$

The defining difference between parametric models and factorial techniques is that the latter separately estimates the price of each process unit, while parametric models only require the number of process units as an input. Consequently parametric models need less project definition and preparation effort compared to factorial methods. Only a very basic flow sheet needs to be available and equipment does not have to be sized. Whether approximate pressures and temperatures are an input is method dependent.

However some disadvantages exist: For example the lack of insight it delivers, what are the major costs within the project? Therefore it is harder to come up with alternatives based on cost estimates. Secondly the definition of a functional unit is vague. A question often arose is whether a simple pumps should have the same dollar value as a furnace in these kind of estimates. Thirdly the factors are based on maxima or averages of temperatures or pressures, therefore it is never able to catch the entire workings of a plant. The parametric models in general always do some concessions to average out these difficulties, consequently the inner statistical variability of this method is large.

Probably because of these issues the method has lost much of it's former popularity. Petley[35] has done the most recent work on comparing and thereafter improving the parametric methods via computer assisted fuzzy matching in 1997. In the 21$^{\text{th}}$ century no innovative steps have been made known to the author of this study. The parametric models still provide an excellent opportunity to compute an order of magnitude estimate with little effort.

2.3.2 Factorial Techniques

To perform a capital cost estimate applying a factorial technique (or factored method) an estimator needs documents containing a preliminary flowsheets and a list of sized equipment. The technique mainly differs from parametric models by the fact that each equipment piece is prices separately. Then factors, most often given as percentages of equipment costs, account for all other direct and indirect costs, see table 2.3. The history and workings of factorial techniques are given in chapter 3 followed by a detailed review.

Although more work than parametric models, the factorial technique does remain popular nowadays. Depending on the method it may give a lot of insight in expense categories, this permits the consideration of alternatives. From more detailed factorial techniques a higher accuracy may be expected compared to parametric methods.

2.4 Equipment Databases & Indices

As denoted in the last section, equipment estimates are the core of factorial estimation methods. In the coming two sections it is explained how to price equipment pieces and how to correct for estimates made in the past.

2.4.1 Equipment Prices

It is generally accepted that the best way to produce equipment price estimates are to ask a vendor for quotations or search for pieces installed recently in similar projects within the company. The sixth-tenth rule by Williams[21], earlier introduced in this work applied on whole plant cost, is identical for estimation of equipment piece prices. The sixth-tenth rule was already widely known, but Williams was the first to publish on the matter. The formula is shown in equation 2.3. Typical capacity units are heat exchanger area, pump flow rate or furnace power consumption. Exponents n are regularly less than unity, consequently costs rise slower than the capacity. This notion is known as the economy of scale.

$$Cost_{\text{ B}} = Cost_{\text{ A}} \cdot \left(\frac{Capacity_{\text{ B}}}{Capacity_{\text{ A}}}\right)^{n} \tag{2.3}$$

Remer and Chai [36][37] have updated and expanded the amount of exponents for equipment items. More recently Symister[38] has extracted exponent values from Aspen Capital Cost Estimator, a popular capital cost estimation software, but the selection only consisted of 10 equipment classes. An interesting method was developed by Chase[39]. In that method exponents of equipment pieces were merged into one exponent for the total plant cost enabling scale-up studies.

Because of time restrictions or unavailability of corporate data, equipment piece price estimates are often extracted from cost databases. Couper[7] has constructed a useful list what to look for:

- **Source of the data**: Is it extracted from vendors or projects?
- **Basis of the cost data**: What is included in the costs?
- **Date of the cost data**: How many years old is this data?
- **Potential errors in the cost data**: What is the standard deviation?
- **Range over which the cost data apply**: Does the range agree my design goals?

Cost data has traditionally been presented in 'cost curves', graphs that depict cost on the y-axis and a capacity parameter on the x-axis. The basis of the data may differ, for example Chilton[40] published cost data for installed equipment thus including freight, auxiliary materials (platforms, foundation, paint, etc.) and instalment labour. A more common way to express equipment cost is on a Free On Board (F.O.B.) basis, which includes buying the equipment piece from a vendor to the point the piece is loaded on a transportation vehicle in a loading port. Freight from the loading port to the site is to be paid by the purchaser.

Improving factorial methods may be done by developing the factors or the equipment database. Extensive separate databases have been published by Pikulik and Diaz[8], who implemented the novelty to show materials, labour, engineering and freight separately for each equipment type. Standard deviation of the cost curves was given in the publication of Hall, Matley and McNaughton[41], bettering the usability of the database. Vatavuk[42] improved databasing by providing not only the cost curves, but also the equations behind them resulting in more precise read-outs. The last 15 years no new cost data has been published in journals. Some organisations do publish for their members, such as the Dutch Association of Cost Engineers (DACE)[43], they publish their latest cost data yearly. Recent book authors like as Seider et al.[17], Woods[44], Turton et al.[45], Sinott and Towler[46] and Couper et al.[47] did publish cost databases. The data in those publications are all in numerical rather than graphical form, which is far more useful in the modern age of computing.

A major issue in the field still exists. There is a persistent lack of shared statistical data significantly delaying scientific progress: Companies are reluctant to share with the goal of maintaining a competitive advantage. The statistical background and accuracy of the newest databases is also unknown.

2.4.2 Cost Indices

The roots of cost indices lie in the 1910's, when the Engineering News-Record (ENR) Construction Index was initiated and since then published in *Engineering News-Record* monthly. It portrays an average of the whole construction business, not necessarily plants. Other popular indices are Chemical Engineering Plant Cost Index (CEPCI) accounting whole chemical plants (see figure 2.2), Nelson-Farrar (NF) Indexes for the petrochemical industry and Marshall-Swift (MS) Process Industry Index focussed on equipment pieces. Updates of CEPCI are published on a monthly basis in the journal *Chemical Engineering*, the MS index was published in the same journal until 2012. NF indexes is published in the journal *Oil and Gas* every month. It is worth noting that these are only a few of the existing indices, an extensive lists of more specialised indices may be found in the work of Remer et al[48].

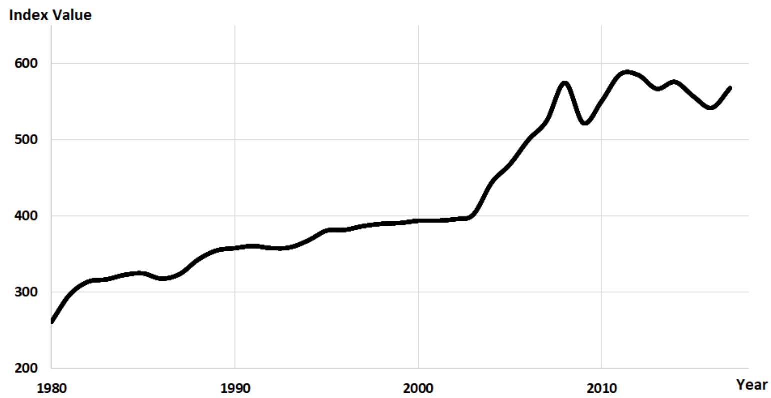

Figure 2.2: Annual averages of the CEPCI in the period between 1980-2017, updates are published monthly in the journal: *Chemical Engineering*[9].

Prices of whole plants or separate equipment pieces may be adjusted using an index of the right choice and equation 2.4. The input is a known cost estimate (project proposal, in-house data, cost database or quotation) from the past, the index value at the year of the known estimate and the value of the new estimate date. Generally projects are build in the future, then the index is extrapolated from known data.

$$\frac{Cost_{\,\mathrm{t=1}}}{Cost_{\,\mathrm{t=2}}} = \frac{Index_{\,\mathrm{t=1}}}{Index_{\,\mathrm{t=2}}} \tag{2.4}$$

Although all cost indices follow a similar trend differences do exist in escalation percentages of each index, because of their different compositions. For example prices of labour may have risen faster than those of steel or concrete, leading to misleading estimates when an estimate for a massive steel apparatus is corrected using the an index mainly correcting for labour. Comparisons between cost indices have been executed by Kohn[49] and Matley[50], they show that the difference is small each year, however because of the accumulative effect of annual corrections it may give larger errors for estimates stretched long periods. It is generally accepted to employ average cost indices for estimates dating back 10 years in time as denoted by Humphreys[10].

The seperate components of CEPCI are published monthly. These are plotted in figure 2.3. It is clearly visible that over a prolonged period the differences in component price escalation are vastly different. Generally the cost for labour has risen less steeply than material costs.

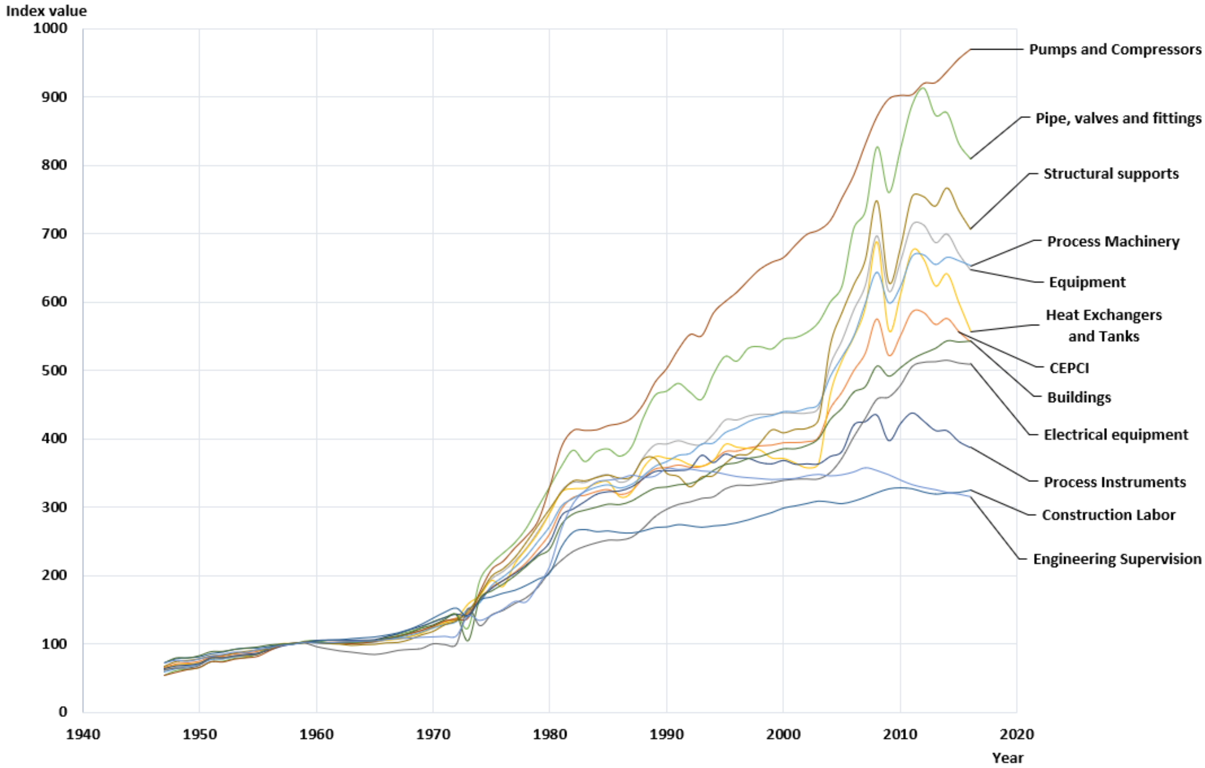

Figure 2.3: Annual averages of the separate CEPCI components in the period between 1947-2016, updates are published monthly in the journal: *Chemical Engineering*[9].

Chapter 3

Factorial Estimation Techniques

A few dozens factorial estimation techniques are found in books and journals from the 1940's onward. This chapter presents an overview these techniques. The discussed methods are divided into classes by the author of this work based on their most apparent characteristics and chronological origin. After an overview of the factorial estimation techniques' history, the works of various innovative authors in each category are elaborated. The chapter is closed with a discussion on the auxiliary facets of factorial estimation including CapEx estimation software.

3.1 An Historical Perspective

The outline of this section is as follows: A brief overview is given on the stance of CapEx estimation for chemical plants before the 'birth' of the factorial technique. Then Lang's work is introduced, the publications that kick-started capital factored estimating. The follow up by other authors is placed into historic context and closely related groups are indicated, which are discussed in greater detail by subsequent sections.

3.1.1 Pré factorial technique estimation methods

Assessment of costs before the start of construction has been a widespread phenomena for centuries. The scientific field of cost estimation of chemical plants has grown substantially after the introduction of Lang's method in 1947. The author of this thesis feels it is out of scope to narrate the whole cost estimation's history back to the beginning of the 20^{th} century, however the setting at that time just before 1947 is interesting.

During this period cost estimation was a time-consuming task. The sixth-tenth rule was known to correlate equipment prizes (although no publication was made yet). The other known method was to estimate costs via turnover ratio's, see chapter 2.3. Two problems occurred with the latter: It is a very rough estimation method not taking into account any design work; specific designs cannot be revised based on costs. Secondly if no turnover data for that product had been published in literature, the technique cannot be used. Therefore chemical engineers turned to a more detailed estimation methods, which are more closely related to accounting. Such assessment methods were explained by for example Prochazka[51] in the Chemical Engineering Handbook of Perry in 1941. An estimation is made by separately assessing each part of a factory construction project, an overview of all the elements is provided on page 8 in table2.3. The requirements for performing such an estimate are high in both engineering work and effort to construct the estimate itself.

An outcry aimed at improving cost estimation methods and cost databases was done in two publication by Eckhardt[52] in 1946 and Williams[53] in 1947, accelerating innovation. Both authors argued that the available cost data was not sufficient to adequately perform effective estimates. Only a fraction of cost data on construction projects were published, which is still a problem today. The most recent at the time were the cost database of Bliss[54] which contained next to equipment prize cost curves also detailed cost relationships on piping including incremental alloy costs. The works of Happel, Aries and Borns[55][56] did also include estimates on buildings, instruments, concrete, structural steel, insulation, and other auxiliaries. For example an estimate for auxiliary buildings may be made on a dollar per square meter of floor area basis.

A second problem indicated by Williams was the basis of data, which frequently differed between publications. He requested to fabricate a standardised way to present cost data. Eckhardt and after him Williams already wrote on the possibility of including auxiliaries as a factor of the equipment costs since they observed a correlation between the two. Although these authors did not developed the factorial methods, their visionary ideas did clear the road for innovation.

3.1.2 The Founding Father: H.J. Lang

In a series of three articles in 1947 and 1948 Lang[57][58][59] published the first factorial method. His proposal was unique for all items not included in the major equipment pieces estimate (see page 19), which were most readily available, could now be estimated as a factor of the total sum of equipment pieces as depicted in equation 3.1. Major equipment pieces refer to directly purchased equipment necessary to perform the conversion tasks in the process part including pumps and processors, excluding storage and utilities. The acquirement of land is not included in the Lang factor F_L and thus also not in the final total depreciable costs C_{TDC}. The total money sum for equipment pieces E_k is on an delivered basis, including freight to site and import taxes.

$$C_{\text{TDC}} = F_{\text{L}} \cdot \sum_{k=1}^{n} E_{\text{k}} \tag{3.1}$$

Lang computed factors distinguished on three cases shown in table 3.1. He argued that the main difference between solids and fluids (or mixed) processes was the amount of piping associated with the main equipment leading to increased costs where more fluids were involved.

Table 3.1: Values of the Lang factors as originally published by H.J. Lang in 1948.

Type of process	$\mathbf{F_L}$ **value**
Solids	3.10
Solids / Fluids	3.63
Fluids	4.74

Reviewing Lang's method

The factorial method by Lang is the most cited technique and presently still in use. However a few notes are in place concerning the reliability of employing his factors. The presumed reachable accuracy was claimed to be 10% compared to detailed estimation techniques. Lang himself already notes that he provides no statistical ground for these factors and requests more experienced estimators to develop more accurate numbers. The database of Lang contained 14 chemical plants of which 2 solid processing, 2 experimental and 3 pilot plants. Only 6 out of 14 were actually constructed, others were only estimated, which shows the concerns on accuracy are undeniable. Presentday it would therefore be unwise to employ the original factors. Updated factors are available as further shown in chapter 3.2.2.
The same chapter explains about a study performed by Cran[60], who proves that Lang's classifications into solids and fluids based on his data are statistically unsound. On the other hand, many other authors are still making these divisions in contemporary literature.

3.1.3 The Literature Tree

Reasonably detailed literature studies on factorial techniques are published by Couper[7], Chauval et al.[61] and Sila[11]. The investigation of literature however remains troublesome for no study exists on the origin of each method and the implications it has for later methods. An attempt is made to fill that gap in this work. Figure 3.1 contains a literature tree showing the innovative authors that contributed to the field, placed in a time period and origin line. The arrows do not necessarily indicate follow-ups on the previous work, they mainly follow consistent features present along that line. In this way the fabric and origin of the literature is categorised and visualised.

If the author disclosed on what type of processes his database or method was formulated, boxes were coloured. Although only three authors wrote that their methods were based on the petrochemical industry, it is likely that more data is based those processes. Not only because that industry has constructed a large amount of plants, but also because other authors indicate they included data from Guthrie or Hand within their own databases.

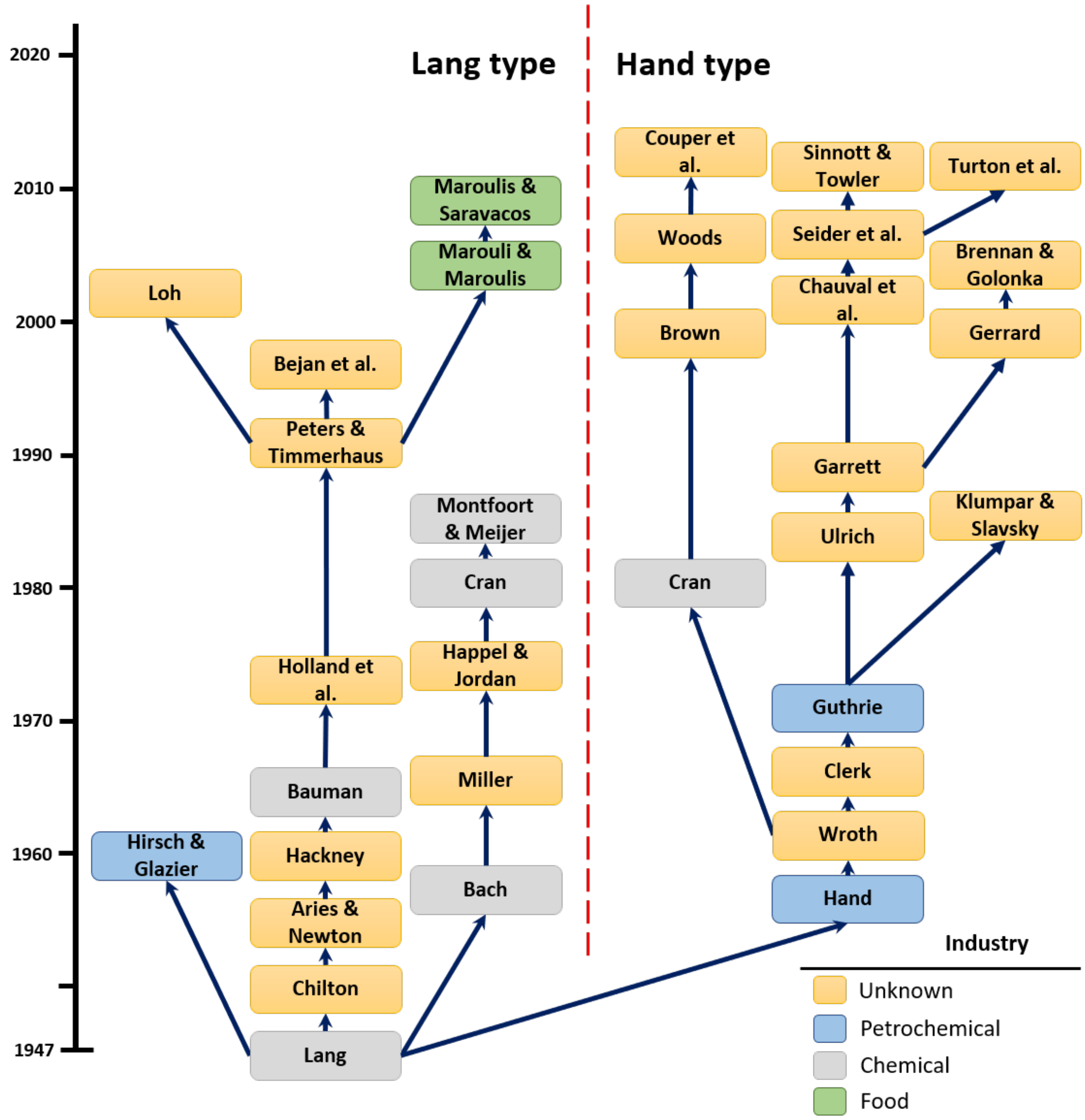

Figure 3.1: Innovative publications on factorial methods put on a timeline and arranged to method characteristics. Colours indicate the type of process upon which the statistics were based.

The major division in literature may be traced back to Lang and Hand. The main difference between the two types is best explained by equation 3.2 and 3.3. The Lang type applies a factor on the sum of equipment cost, while the Hand type applies a unique factor on each equipment piece and only sums thereafter. Note this is only the core equation of a method, factors may be calculated, tabulated or otherwise determined in various ways and additional factors may be necessary to finish the estimate.

$$C = F \cdot \sum_{k=1}^{n} E_{\mathrm{k}} \tag{3.2}$$

$$C = \sum_{k=1}^{n} F_{\mathrm{k}} \cdot E_{\mathrm{k}} \tag{3.3}$$

The two types may be further organised into subtypes, these are shown in table 3.2. In the following sections of this thesis every category is highlighted. The works of the authors are elaborated and wherever possible translated from the original format to equations, for in the current computer age these can most easily be employed for consecutive applications. Nomenclature varies greatly in literature, these were adapted such that common principles are named alike.

Worked out examples may improve understanding of the methods, therefore an example case study is defined. The worked out examples of the Lang type are included in appendix B, the Hand type in appendix C respectively. It is hard to conclude anything on the accuracy of the methods based on these worked out examples, for a statistical test would require more than one case as data input. Nevertheless a short discussion on the topic is included in chapter 4.

Table 3.2: Factorial methods organised per category, see figure 3.1

Lang Type	*Publications*	*Chapter*
An Art rather than a science	Chilton[40], Aries & Newton[12], Hackney[62], Bauman[18] and Holland et al.[63]	3.2.1
Improved Lang factors	Peters & Timmerhaus[13], Bejan et al.[64], Marouli & Maroulis[65] and Maroulis & Saravecos[66]	3.2.2
Battery limit estimates	Bach[67], Miller[68], Happel & Jordan[69], Cran[60] and Montfoort & Meijer[70]	3.2.3
Other Lang type variants	Hirsch & Glazier[71] and Loh et al.[72]	3.2.4
Hand Type	*Publications*	*Chapter*
Original Hand type methods	Hand[73], Wroth[74] and Clerk[75]	3.3.1
Separate Instrument Estimates	Cran[60], Brown[76][77], Woods[44] and Couper et al.[47]	3.3.2
Guthrie type	Guthrie[78][79], Ulrich[80] and Garrett[81]	3.3.3
Labour Focussed	Klumpar & Slavsky[82][83][84][85]	3.3.4
The IChemE method	Gerrard[15] and Brennan & Golonka[86]	3.3.5
Modern databases	Chauval et al.[61], Seider et al.[17], Sinnott & Towler[46] and Turton et al.[45]	3.3.6

3.2 Lang Type

The Lang type methods are characterised by the given equation 3.1 on the previous page, being that the the sum of equipments is multiplied by a factor. It does not have to be a single factor as will be shown in the following sections, the four groups of Lang type estimates are explained in more detail in the same order shown in table 3.2.

3.2.1 Method Group: Estimation is an Art Rather than a Science

The statement that estimation is rather an art than a science is best explained by first introducing the origin of this method: the work of Chilton[40] in 1949. Estimators during this period saw the potential of Lang's method, however there was a feeling that this was just an order of magnitude analysis. For a more accurate measurement a non-adaptable factor would not suffice, a judgement call from the estimator himself was a necessity.

C.H. Chilton

Chilton's work[40] is summarised by equations 3.4 and 3.5. To compute the total physical cost, factors defined as fractions of installed equipment cost E are applied. The factors are distinguished by subscripts: Piping associated with equipment pieces *P1*, other outside piping lines *P2*, manufacturing buildings B, auxiliary facilities F and instruments I.

To account for indirect costs a second set of factors are applied on the total physical cost for engineering and construction *E&C*, contingencies C and factor to adjust for size, a size factor *SF*. Note how all factors could be merged to find an equation identical to Lang's formula.

$$C_{\text{physical}} = (1 + F_{\text{P1}} + F_{\text{P2}} + F_{\text{B}} + F_{\text{F}} + F_{\text{I}}) \cdot \sum_{k=1}^{n} E_{\text{k}} \tag{3.4}$$

$$C_{\text{TDC}} = (1 + F_{\text{E\&C}} + F_{\text{C}} + F_{\text{SF}}) \cdot C_{\text{physical}} \tag{3.5}$$

Typical values are given in Chilton's publication and are reproduces in table 3.3 and 3.4. The estimator needed to determine whether a low of high value (or anything in between) was applicable for this particular design, no more extensive guidelines than those shown in the table were given. Note how piping costs are affected by the type of process similar to Lang's method.

Table 3.3: Typical values of the direct cost factors applied by Chilton[40], buildings and facilities may also be set at 0% when none are necessary.

Factor	Low	Average	High
P1	Solids processing plant **7 - 10%**	Mixed processing plants **10 - 30%**	Fluids processing plants **30 - 60%**
P2	Close to integrated facilities **0 - 5%**	Separate processing units **5 - 15%**	Scattered processing units **15 - 25%**
B	Outdoor construction **5 - 20%**	Mixed construction **20 - 60%**	Indoor construction **60 - 100%**
F	Minor additions to site **0 - 5%**	Major additions to site **5 - 25%**	Facilites at a new site **25 - 100%**
I	Little or no automatic control **2 - 5%**	Some automatic controls **5 - 10%**	Centralised complex controls **10 - 15%**

Table 3.4: Typical values of indirect cost factors applied by Chilton[40].

Factor	Low	Average	High
E&C	Straightforward engineering Average labour/materials ratio **20 - 35%**	-	Complex engineering High labour/materials ratio **35 - 50%**
C	Firm process **10 - 20%**	Subject to change **20 - 30%**	Speculative process **30 - 50%**
SF	Large commercial unit **0 - 5%**	Small commercial unit **5 - 15%**	Experimental unit **15 - 35%**

Reviewing Chilton's Method

Based on the amount of successive authors one may conclude that Chilton's method was very successful at the time. The belief that estimation is an art rather than a science is clearly visible in this method. And indeed theoretically the potential accuracy of the method is high, however it is very much dependent on the experience and skilfulness of the estimator. And even a skilled estimator might find it difficult to asses a novel process at the feasibility stage. The prepared information necessary to perform the estimate is higher compared to Lang's method; one needs to prepare layouts for equipments placing, buildings and have an idea of the extend of piping and instruments. If only little information is available the estimating process is highly speculative, the ranges to choose from are broad. It is unknown whether the ranges are based on statistical data from previous constructed projects or whether these resemble the professional know-how of Chilton.

Another drawback is that the instructions are not clear: When is a process firm? When are facility additions to a site minor or major? When is a unit large or small? For Lang's method it is known that not all parameters are captured in the single factor. For Chilton's method there is always room for discussion potentially leading to misinterpretations of the method's accuracy, which may not be captured in a single figure.

It is not recommended to apply Chilton's method in contemporary estimates for two reasons: The value of factors are outdated and have changed over the course of years. This is for example clear in the instrumentation factor, those will have a higher value in contemporary projects. Secondly the basis of direct cost factors is on installed equipment prices. Although Chilton provides (outdated) cost curves for 22 types of equipment, modern databases are mostly based on F.O.B. prices providing an additional bump in employing this method.

R.S. Aries & R.D. Newton

Since all methods in this group are very similar to Chilton's, the explanation less detailed. Examples of every Lang type method are to be found in appendix B for additional clarification.

$$C_{\text{physical}} = (1 + F_{\text{IL}} + F_{\text{P}} + F_{\text{I/L}} + F_{\text{I}} + F_{\text{E}} + F_{\text{B}} + F_{\text{Y\&L}} + F_{\text{U}}) \cdot \sum_{k=1}^{n} E_{\text{k}} \tag{3.6}$$

$$C_{\text{DPC}} = (1 + F_{\text{E\&C}}) \cdot C_{\text{physical}} \tag{3.7}$$

$$C_{\text{TDC+land}} = (1 + F_{\text{CF}} + F_{\text{C}}) \cdot C_{\text{DPC}} \tag{3.8}$$

Table 3.5: Subscripts of factors associated with the equations 3.6 to 3.8.

B	Buildings	IL	Installation Labour
C	Contingencies	I/L	Insulation/Lining
CF	Contractor's Fee	P	Piping
E	Electrical Installations	U	Utilities
E&C	Engineering and Construction	Y&L	Yard Improvements and Acquirement of Land
I	Instruments		

The method of Aries and Newton[12], published in 1955, deviates from Chilton's in a few ways, see equation 3.6 to 3.8 and additionally table 3.5. The basis of the sum of equipment is purchased equipment *E*. Compared to Chilton piping now is merged to a single account, installation labour is added for the basis of equipment is not installed. Also added in separate accounts are insulation, electrical, contractor fee's, land improvements and the costs of land. Chilton's factor for size is abandoned, however some of the factors such as buildings *B* and engineering and construction *E&C* are a function of dollar value, which is a measure of plant size. See for example table 3.6, which shows how to determine the factor value for buildings.

Table 3.6: Determining the building factor F_B in Aries and Newton's method[12], dollar values are based on 1954 values.

Equipment Cost	Outdoor	Indoor
Less than $250,000	50%	80%
$250,000 - $1,000,000	40%	65%
More than $1,000,000	30%	50%

Other factors may be determined in a similar fashion as in Chilton's method. For some like utilities F_U a choice out of three is provided: 25% for a minimum of additional services and 40% or 75% for average or complete new services respectively. Other like lining are static (8%). Interestingly the factor for installation labour is a function of equipment types (which is actually a handprint of Hand's[73] method before the actual introduction), but may also be taken as an average of 43%.

Reviewing Aries & Newton's Method

The ranges of factors are smaller compared to Chilton's method. Also the descriptions when to apply high values or low values are more clear in Aries and Newton's method. The division into more cost categories (including distinguishing between materials and labour) gives a better idea on what the major cost items are. Whenever the estimator has more information on a certain cost item for example on buildings (floor, wall and roof design), it is possible to include it improving the accuracy.

The choice to multiply costs for contractor's fee and contingencies with the direct plant costs (DPC) including engineering and construction is sensible. The inclusion of land inside the physical costs is an unusual practise, for the indirect costs factors do not correlate well with land cost. The error however is not large for land is a small fraction of the costs.

A major issue is the term 'purchased' equipment. It is unknown whether this is only the purchase of the equipment item locally, or it is a F.O.B. price or it also includes freight to site and import taxes.

J.W. Hackney and H.C. Bauman

Although the method by Hackney[62] and Bauman[18] are considered to be falling within this group, their innovative value is considered to be low. A more elaborate description on the two methods is found in appendix E.

F.A. Holland, F.A. Watson & J.K. Wilkinson

In 1974 Holland, Watson and Wilkinson[63] were the first to mix the concept introduced by Lang with Chilton's work. The Lang factor was divided into the product of three factors: ϕ_1, ϕ_2 and ϕ_3, shown in equation 3.9. The equipment price sum is based on delivered to site prices, the factor ϕ_1 is used to convert to installed equipment costs used in Chilton's method. The values range of values is small: 1.45, 1.39 and 1.47 for solid, mixed and fluid processing respectively.

$$C_{\mathrm{TDC}} = \phi_1 \cdot \phi_2 \cdot \phi_3 \cdot \sum_{k=1}^{n} E_{\mathrm{k}} \tag{3.9}$$

The second factor ϕ_2 is the direct cost factor and ϕ_3 accounts for all indirect costs. These are expanded in equations 3.10 and 3.11. The subscripts but also the values are identical to those of Chilton's method on page 19 given in table 3.3 and 3.4.

$$\phi_2 = 1 + F_{\mathrm{P1}} + F_{\mathrm{P2}} + F_{\mathrm{B}} + F_{\mathrm{F}} + F_{\mathrm{I}} \tag{3.10}$$

$$\phi_3 = 1 + F_{\mathrm{E\&C}} + F_{\mathrm{C}} + F_{\mathrm{SF}} \tag{3.11}$$

Reviewing Holland, Watson & Wilkinson's Method

A critical review of the method published by Holland, Watson and Wilkinson (1974), it is noticed that the only difference with Chilton's method[40] is the converting factor ϕ_1 between delivered and installed equipment. Other factors are directly copied from Chilton. This is fruitful because these prices are more easily found in literature or via vendor quotes. The statistical basis of the factor's value is unknown, though the values are very close to Lang's or Aries and Newton's[12] instalment factors[59]. Still difficulties present in Chilton's original method remain, such as the need of an experienced estimator which defines the 'Art rather than a Science' movement. It is claimed that the method's accuracy 15%, which is regarded at least doubtful by the author of this thesis.

Other novelties, not directly related to the technical details of the method, may be recognised as well. The paper is first in the Chilton line of work to show it's method in formula's instead of tables, probably this is due to the introduction of the computer. Secondly the link to Lang by expanding the Lang factor (or collapsing the Chilton factors) is innovative. Before the Lang factor was set and not improved, after this publications many authors derived their own Lang factors based on information available.

Summary: Estimation is an Art Rather than a Science

The group is defined by the large influence of the estimator on the final result, which makes the methods rather difficult to perform for inexperienced estimators. The origin may be traced back to Chilton's work[40] followed up by various authors discussed in the text. The basis on which equipment prices were determined varied (purchased, F.O.B. or installed) and proved to be inconvenient, which was aimed to be solved by Holland, Watson and Wilkinson[63] by providing conversion factors. All factored methods eventually worked on installed equipment prices thus including labour. Cost categories factors differed between publications (land, electrical, utilities, etc.), raising the question whether it was included or excluded in each method.

In the '70's the 'Art rather than a Science' movement came to a close. Interestingly a quote from Stallworthy[28] in 1970 simultaneously denies and reveals this change in scope: *"Do not be misled by the increasingly "scientific" approach to this subject. Estimating is still an art, rather than a science."*

3.2.2 Method Group: Improved Lang factors

Contemporary methods mostly apply rigid factors that are not open for interpretation. It may be caused by the increased focus on approaching the field in a scientific manner; employing averages instead of the estimator's gut feeling. However as long as standard deviations and statistical background in amount of plants, type of plants, age of data and reliability are not shared in publications, the scientific basis is not secured.

M.S. Peters & K.D. Timmerhaus

The method by Peters and Timmerhaus[14] is similar to the method of Lang. It employs a Lang factor discriminating between solid or fluid process types. It does give more insight into various cost items than the original method as clearly visible in table 3.7 which shows factors as a fraction of equipment cost already delivered to site. The information of the table may be converted to equations leading to equation 3.12 to 3.15.

The costs displayed are for project addition to an existing site (brown-field). Peters and Timmerhaus note that costs for a project at a completely undeveloped site may be 100% higher, because of the increased need of service facilities, storage, terminals, etc. The costs for contractor's fee and contingency are approximated to be 5% and 10% of DIC respectively. Working capital is estimated at 15% of TDC. So if an the estimate is subject to manual change, for example when costs for piping are wished to be decreased, the latter percentages can still be applied, changing the numbers in table 3.7 for these cost items, but not in equations 3.14 and 3.15. It is also possible to only apply the end values (for example TDC) of the table in a Lang type of equation.

$$C_{\text{DPC}} = (1 + F_{\text{IL}} + F_{\text{I}} + F_{\text{P}} + F_{\text{E}} + F_{\text{B}} + F_{\text{Y}} + +F_{\text{F}} + F_{\text{L}}) \cdot \sum_{k=1}^{n} E_{\text{k}} \tag{3.12}$$

$$C_{\text{DIC}} = C_{\text{DPC}} + (1 + F_{\text{E\&S}} + F_{\text{CE}}) \cdot \sum_{k=1}^{n} E_{\text{k}} \tag{3.13}$$

$$C_{\text{TDC+land}} = (1 + F_{\text{CF=5\%}} + F_{\text{C=10\%}}) \cdot C_{\text{DIC}} \tag{3.14}$$

$$C_{\text{TCI}} = (1 + F_{\text{WC=15\%}}) \cdot C_{\text{TDC+land}} \tag{3.15}$$

Table 3.7: The method of Peters and Timmerhaus[14] displayed in tabular form.

Cost item	**Process type**		
	solids	*solids/fluids*	*fluids*
Delivered equipment	**1.00**	**1.00**	**1.00**
Equipment installation labour	0.45	0.39	0.47
Instrumentation and controls	0.09	0.13	0.18
Piping	0.16	0.31	0.66
Electrical installations	0.10	0.10	0.11
Buildings	0.25	0.29	0.18
Yard improvements	0.13	0.10	0.10
Service facilities	0.40	0.55	0.70
Land	0.06	0.06	0.06
Direct plant cost (DPC)	**2.64**	**2.39**	**3.46**
Engineering and supervision	0.33	0.32	0.33
Construction expenses	0.39	0.34	0.41
Direct and indirect costs (DIC)	**3.36**	**3.59**	**4.20**
Contractor's fee	0.17	0.18	0.21
Contingency	0.34	0.36	0.42
Total depreciable costs (TDC)	**3.87**	**4.13**	**4.83**
Working capital	0.68	0.74	0.86
Total capital investment (TCI)	**4.55**	**4.87**	**5.69**

Reviewing Peters & Timmerhaus' Method

The numbers in table 3.7 are published in the 4th edition of the book in 1991, previous and later editions show only minor differences. No information on the statistical basis is available except for the fact that projects between $1 and $20 million American dollars were considered. It is no wonder that Peters and Timmerhaus' method has been cited many times: It is easy to apply, it is one of the most recent Lang type methods and the adaptability is high. If an estimator has a more detailed estimate of a cost item such as land, building, piping, etc., it may easily be incorporated into the final estimate. In contemporary literature no serious attempts are published on improving the original numbers, for example in 2015 the U.S. Department of Energy[87] and in 2017 El-Halwagi[88] still employed the same factors taken from the fifth edition of Peters, Timmerhaus and West[89]. The main difference with the fourth edition is an increase in instrumentation costs and the addition of a legal expense cost item rated at 4% of equipment cost.

The method has disadvantages. For example the inclusion of land, although it is only a small amount, within DPC is impracticable and is better be incorporated in the later step from TDC to TCI. The choice to base the factors on delivered equipment costs instead of F.O.B. prices generates a method that is less straightforward to apply. Another complication is that the method applies to a developed existing (brown-field) site raising the questions on what is exactly already present at the location. For example: What transportation systems or utilities are already present or included in the yard improvement or service facility cost items?

Table 3.8: Values of the Lang factors published by Lang[59] in 1948, Peters and Timmerhaus[14][89] in 1991 and 2003 and Sinnott and Towler[46].

Type of process	**Lang**	**Peters & Timmerhaus**		**Sinnott & Towler**
	1948	*1991*	*2003*	*2012*
Solids	3.10	3.80	3.90	4.55
Solids / Fluids	3.63	4.06	4.21	6.05
Fluids	4.74	4.77	4.97	6.00

It is interesting to compare Lang's factors and the work of Peter and Timmerhaus (subtract land), see table 3.8. Sinnott and Towler[46], see page 49 have been added as the latest updated resource available. A rising trend in Lang factors is clearly visible, although interestingly the factor for fluid processes has not changed significantly over a period of more than 40 years, and is overtaken by the solid-fluid processes. The reason of the increased Lang factor may only be speculated upon since Lang does not provide data on each cost item. It might be due to the observed decrease in piping costs (14% solids, 36% mixed and 86% fluids in 1948) combined with a simultaneous increase in other auxiliary costs for example instrumentation or a decrease in equipment cost. Factors published by Sinnott and Towler in 2012 show a larger rise of the factor. This is partly due to a large increase in off-site costs. It is unclear whether these costs actually increased or whether different types of projects were considered.

A. Bejan, G. Tsatsaronis & M. Moran

The improvements made by Bejan et al.[64] in 1996 were based on data from literature sources, Peters and Timmerhaus in particular. The data was combined and averaged leading to Lang factors based on a purchased (not including shipment, taxes and installation) equipment basis. Table 3.9 shows the resulting Lang factors for both new systems and expansion for TDC (may be compared to Lang factors) and TCI, the latter includes start-up costs, working capital, costs of licensing, research and development and allowance funds during construction.

$$C_{\mathrm{TDC}} = F_{\mathrm{TDC}} \cdot \sum_{k=1}^{n} E_{\mathrm{k}} \tag{3.16}$$

Table 3.9: Factors published by Bejan et al.[64]

	New system	Expansion
TDC	4.30	2.83
TCI	6.32	4.16

Reviewing Bejan, Tsatsaronis & Moran's Method

The classifications provided are confusing, for the term 'new system' is somewhat arbitrary. Comparing the values of the numbers to Peters and Timmerhaus 'new system' probably refers to a brown-field project. The difference between new system and expansion is motivated by the difference in off-site costs, which include land, civil structural and architectural work and service facilities. Note that the solid or fluid process discrimination is dropped and averaged out. The method is proximate and merely an order of magnitude analysis may be obtained.

A.Z. Marouli, Z.B. Maroulis & G.D. Saravacos

In 2005 Marouli and Maroulis[65] published a Lang factor for the food industry. Inspired by the work of Peter and Timmerhaus the factor was divided into a civil work factor F_{CV}, including installation labour, piping, instrumentation and control, electrical equipment, engineering and supervision. And a mechanical and electrical work factor $F_{M\&E}$, including buildings, structures and yard improvements. This leads to equation 3.17. The value of the Lang factor (without contingencies) reported is 1.80 as an average for the food industry, the distribution of costs is found to be $F_{CV} = 0.45$ and $F_{M\&E} = 0.35$.

$$C_{\mathrm{TDC}} \;=\; (1 + F_{\mathrm{CV}} + F_{\mathrm{M\&E}}) \;\cdot\; \sum_{k=1}^{n} E_{\mathrm{k}} \tag{3.17}$$

CapEx and OpEx cost data from 33 industrial food process plants is published in 2007 by Maroulis and Saravacos[66]. A Lang factor is extracted per process between 1.41 and 2.72 for a protein recovery a baker's yeast production plant respectively. The average value is 1.82 (now including contingencies), no cost items are separately indicated.

Reviewing Marouli, Maroulis & Saravacos' Method

In earlier work of Maroulis and Saravacos[90] (2003) it was shown that the Lang factor for food plants is lower than those reported in the chemical industry, mainly caused by high equipment costs due to the use of stainless steel and almost no incremental costs in auxiliary pieces. This clearly shows that the use of a Lang factor is truly process type specific and that applying Lang factors should be done with the complexions of a particular process in mind. Unfortunately no other food industry specific factorial methods have been developed yet, which would have great potential improving estimates in this field. The same is to a lesser extend (because of more similarities to traditional industry) true for biochemical plants.

Although the methods for the food industry were published in the 21$^{\mathrm{th}}$ century, the cost data for the analysis is not. It is admirable that the raw data is made known, however the data is extracted from Bartholomai[91] (1987), which makes the data too aged for accurate estimates.

Summary: Improved Lang Factors

Peters and Timmerhaus[14] are the main representatives of this category. The Lang factor was split to give estimates for every cost item. This improved the influence an estimator has on costs for each item without comprising accuracy which was the problem with the 'art rather than a science' group. In general a rising trend in Lang factor value is visible.

Bejan et al.[64] proposed distinguished Lang factors for expansions and Maroulis, Marouli and Saravacos[65][66] showed that industry specific Lang factors may greatly enhance estimates for the food industry. These authors have diversified and specialised the Lang factors showing that much may still be gained in other industrial areas or specialised situations.

3.2.3 Method Group: Battery Limit Estimates

The following methods are grouped because of one dominant observation, namely that particular off-site constructions do not correlate well with equipment costs. Therefore the term 'battery limit estimate' was introduced. Note that there are many similarities present with the other groups 'art rather than a science' and 'improved Lang factor', those are indicated wherever applicable.

N.G. Bach

The term 'battery limits' (BL) does not originate from Bach's mind but from the American Association of Cost Engineers. However he was together with Hand[73] one of the first persons to implement it in a factorial method in 1958. Bach's method[67] applies to fluid plants since this was the only type of process handled at his employer: Monsanto. He was able to share raw data of 32 construction projects, also providing valuable information for later method developers.

Figure 3.2 reveals the division of a plant in geographical units: Process units, utility units, storage & handling and services. Battery limits are indicated by dashed border lines, thus excluding services. Note that this definition of battery limits has shifted over time towards only including the process units.

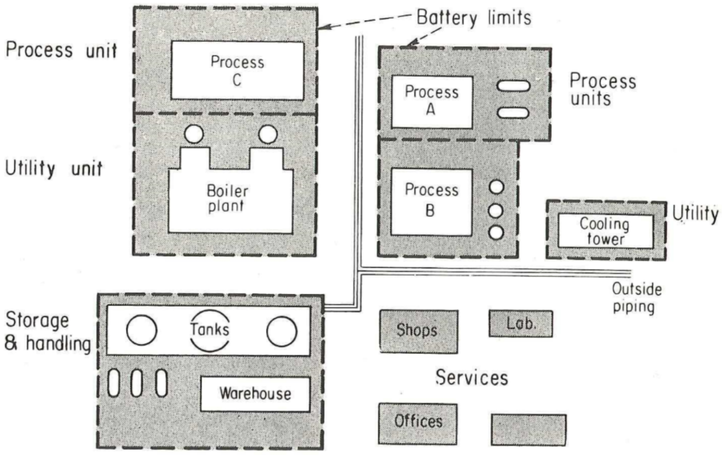

Figure 3.2: The original pictogram by Bach[67] showing the definition of battery limits.

The innovative idea of Bach was to associate different specialised Lang factors for each battery limit part. One should estimate each unit separately and afterwards sum to find the total investment. Calculated averages from the data of Bach plus standard deviations are given in table 3.10, the corresponding division into subfactors (civil, piping, etc.) of these Lang factors are given in figure F.1 in appendix F.

Table 3.10: Lang factors plus standard deviations computed from 8 process units, 8 utility units, 6 storage handling units and 5 addition or alterations projects published by Bach[67].

	Process Units	**Utility Units**	**Storage & Handling**	**Additions or alterations**
Lang factor: F_{BL}	3.13 ± 0.54	2.13 ± 0.35	3.44 ± 0.93	3.20 ± 1.11
Coefficient of variation	16%	17%	27%	35%

Bach advocates, in the condition that enough information is available for the project, to instead of averaged Lang factors use rules of thumb to make an estimate of each subfactor, which he provides in the article. Because of the relatively large standard deviation of average subfactors an increase in accuracy may be expected if progressed skilfully, this is very similar to the idea of Chilton[40] elaborated in chapter 3.2.1. Factors might change by approximately a factor two in the high and low side.

A summary of Bach's method computing the total direct costs within battery limits $C_{BL\ directs}$ is represented by the set of equations below on a delivered equipment basis: 3.18 and 3.19. The latter equation is given for the process units PU estimates, but is identical in estimating the utilities U, storage and handling $S\&H$ or alterations/additions A/A part. The estimator may implement the factor from table 3.10 directly. Otherwise the factor is compiled from the factors indicated in figure F.1 and the directions given in Bach's article.

$$C_{\text{BL direct}} = C_{\text{PU}} + C_{\text{U}} + C_{\text{S\&H}} + C_{\text{A/A}} \tag{3.18}$$

$$C_{\text{PU}} = F_{\text{PU}} \cdot \left[\sum_{k=1}^{n} E_{\text{k}}\right]_{\text{PU}} \tag{3.19}$$

Reviewing Bach's Method

The division of Lang factors into factors for each geographical location within a constructed plant is an excellent idea for it is clear from the data provided by Bach that differences are large. Specialised Lang factors are preferred as shown before, since they may increase the accuracy. A major concern is the lack of location definitions. For example: What is to be included in major equipment in the storage and handling part? Further the method lacks estimation procedures considering items outside of battery limits and indirect costs, limiting the applicability of the technique.

The procedure to estimate each cost item separately mimics, though is not identical to, the work of Chilton[40] or Aries and Newton[12] and may therefore also be placed in the 'art rather than a science' group.

Table 3.10 shows a high standard deviations especially for the storage & handling and additions or alterations parts. This is due to a combination of inner spread in the data and a low amount of projects. Figure F.1 shows large differences in costs for various cost items (especially piping above ground) between categories, this is a justification for distinguished factors for each geographical location.

The finished estimate $C_{BL\ directs}$ contains all direct costs for the battery limits investment. In order to compute indirect costs Bach refers to O'Donnell[92], who provides a graph relating total plant costs to indirect costs for plants processing mainly fluids. Although the method merely provides rough projections, it has been a popular method from the '50's to 70's for no alternative paths to estimating indirect costs were developed. Nowadays it is considered to be outdated.

C.A. Miller

The definitions of geographical area's within a plant introduced by Bach are expanded by Miller[68], these are in line with what is reported in chapter 2.2. The factorial technique deviates from Bach's by solely estimating the process units in detail and thereafter roughly assessing the other three location categories. Confusingly the term 'battery limits' now refers to the process units, not including storage & handling, utilities and services. This has since Miller's publication in 1965 been considered good practise, thus it was chosen to adopt the terminology in this thesis work, further elaborated in appendix H.

Miller's method is of higher complexity than previously discussed methods. The fundamental innovation made by Miller is the idea that auxiliary item (piping, supports, etc.) costs displayed by a factor are a function of the average equipment costs, see figure 3.3. Three causes are identified, in which equipment costs do rise while other costs do not rise at the same rate as the equipment cost: Materials of construction, operating pressure and equipment size.

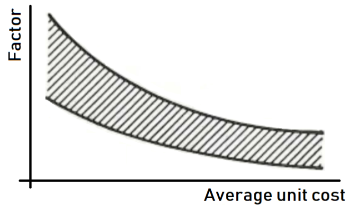

Figure 3.3: A sketch of Miller's position of varying the factor with equipment cost, the figure is adapted from his article[68].

The estimation system is represented by equations 3.20 to 3.22. First the total sum of main plant items are computed and averaged. In Miller's article factors are published that vary along seven columns depending on the average cost of plant items. Thus for an estimate of one project only a single column is applied; relatively more expensive equipment pieces result in lower factors.

Secondly the factors are not based on the main plant items regularly showing up on a flow sheet or equipment list, but should according to Miller also include miscellaneous unlisted equipment *MUE* for which a factor is applied providing the term basic equipment *BE*.

Thirdly factors are employed to find the battery limit investment similar to other methods, all subscripts are to be found on page 75. Insulation is split into an equipment and piping part. Miscellaneous *M* items are among other paint and site preparation. An estimator will need experience to find the proper values, for only broad ranges are provided in each column. Building estimates require an idea on the type of structures.

$$C_{\text{BE}} = F_{\text{MUE}} \cdot \sum_{k=1}^{n} E_{\text{k}} \tag{3.20}$$

$$C_{\text{BL}} = (1 + F_{\text{IL}} + F_{\text{SU}} + F_{\text{P}} + F_{\text{I/L-E}} + F_{\text{I/L-P}} + F_{\text{E}} + F_{\text{I}} + F_{\text{M}} + F_{\text{B}}) \cdot C_{\text{BE}} \tag{3.21}$$

$$C_{\text{DPC}} = (1 + F_{\text{S\&H}} + F_{\text{U}} + F_{\text{S}}) \cdot C_{\text{BL}} \tag{3.22}$$

The outside battery limit costs are not estimated based on equipment costs as done by Bach[67], but with factors working on the total process battery limit cost. These factors are approximate, and may be selected based on available information. For example what kind of compressed air, distribution systems, sewers, warehouses, offices, railroads, etc. are necessary to install.

The final estimate only provides the direct plant costs for either solely the battery limits or when equation 3.22 is included for grass root plants only. Excluded are all indirect costs (including contingencies), catalyst and sales taxes.

Reviewing Miller's Method

Miller reports his estimates to be within 15% accurate. Because of the complexity, the rough estimating technique for estimates other than battery limits, and the high amount of 'estimator's feel' it is difficult to achieve this accuracy. This makes this estimate method fit right into the 'art rather than a science' group. The low and high value ranges may be applied to find an average, low and high estimate creating a final estimate band rather than a number, which is a good idea to represent the uncertainty present in the estimate.

The idea of adapting the value of factors to equipment average value is both innovative and useful. Many authors (only Hand type) have followed the same reasoning after Miller's publication. The fact that cost are averaged is dubious especially in small sized projects.

The applicability of Miller's method in contemporary estimates is very limited. Both because of the aged factor values and the fact that the division of columns based on the average equipment cost in 1958 dollar values. Additionally indirect costs and sales tax on equipment and auxiliary items are not included which may be a significant part of the total costs.

J. Happel & D.G. Jordan

The following method is based on the second edition of the book (1975) by Happel and Jordan[69], their cost scheme may be illustrated by equations 3.23 and 3.24. The latter is identical to the collapsed version of Aries and Newton's[12] equations, 3.7 and 3.8, containing factors for engineering and construction overheads *E&C*, contractor fee's *CF* and contingencies C, which are set at 30%, 10% and 10% respectively. The factors in equation 3.23 work on the sum of installed equipment costs, Happel and Jordan provide numbers to compute installation labour for different equipment types when necessary, varying between 10 and 35% of equipment costs. If for some reason it is more convenient to add pieces already including auxiliary materials and labour, for example based on previous projects or a complex tailored reactor, it is possible to add it as $C_{special}$.

$$C_{\text{physical}} = C_{\text{special}} + (1 + F_{\text{I/L}} + F_{\text{P}} + F_{\text{FO}} + F_{\text{B}} + F_{\text{S}} + F_{\text{FP}} + F_{\text{E}} + F_{\text{PA}}) \cdot \sum_{k=1}^{n} E_{\text{k}} \quad (3.23)$$

$$C_{\text{BL}} = (1 + F_{\text{E\&C}}) \cdot (1 + F_{\text{CF}} + F_{\text{C}}) \cdot C_{\text{physical}} \quad (3.24)$$

More differentiated factors are introduced compared to previous methods: insulation *I/L*, piping *P*, foundations *FO*, buildings *B*, support structures *S*, fireproofing *FP*, electrical work *E* and paint and clean-up *PA*. The factors are build up from material *M* and labour *L* component shown by equation 3.25. Values of these components are provided in table G.1 in appendix G. Note the ranges are small compared to methods discussed in previous sections.

$$F_{\text{A,B,C,...}} = M \cdot (1 + L) \quad (3.25)$$

The values for labour prices are based on carbon steel equipment. The fraction should be lowered if more expensive alloys are installed, this line of though is similar to Miller's[68].

Reviewing Happel & Jordan's Method

Interestingly in this method the cost account for fireproofing has been added compared to other methods before 1975. Probably this is inspired upon publications from other method groups, for example the publications by Hand[73] elaborated upon in chapter 3.3. However it does raise the question whether these costs were included in for example the method by Chilton[40].

The value ranges are quite small approaching methods similar like Peters and Timmerhaus'[14], that apply a static factor. Indeed at the time of writing the book a transition period between the 'Art rather than a science' movement and more rigid ways of estimating is visible.

A note made by Happel and Jordan themselves is that in the past years labour prices have risen faster than those for materials, therefore requesting the user to use the higher values for labour wherever applicable. This immediately exposes the weakness of splitting: The values age faster creating a need to have recent data. Although splitting materials and labour may give useful insight into cost accounts, it is doubtful whether (even with recent data) increases the accuracy.

J. Cran

In 1981 Cran[60] performs a statistical study on the original Lang factors and his own newly derived Lang factors from 90 chemical plants. The results of the latter are shown in table 3.11. Note that these new factors do not include costs for off-sites (amenity buildings, storage facilities, utilities and services including site improvements, transportation infrastructure and miscellaneous buildings), which Cran argues do not correlate well with equipment cost, since they are largely determined by the environment, product type and the market. This leads to equation 3.26, in which C_O are the costs for off-sites and F_{BL} the factor for investments within battery limits.

$$C_{\text{TDC}} = C_{\text{O}} + F_{\text{BL}} \cdot \sum_{k=1}^{n} E_{\text{k}} \tag{3.26}$$

Table 3.11: Cran's improved Lang factors for battery limit investments based on 90 plants.

Type of process	$\mathbf{F_{BL}}$ **value**	**Standard deviation**
Solids	3.00	± 0.61
Solids / Fluids	3.04	± 0.81
Fluids	3.15	± 0.81
Unclassifiable	3.39	± 0.99
All classes	3.19	± 0.86

Reviewing Cran's Method

The point Cran is eager to make is that although the F_B values differ slightly between solids and fluids, the standard deviation is too high to acknowledge their differences. Therefore it is not statistically sound to distinguish between the classes. Because of these uncertainties, he argues it is better to employ the average value in all cases until more specialised factors have been developed. It is a somewhat surprising result for the distinction in these process classes, originating from Lang[59], have been widely accepted in factorial method literature and continues to be applied after Cran's publication.

A note should be made: Cran provides no short cut way to estimate the off-site investment separately, according to Cran an approximate number of 15% of direct battery limit costs could be employed. Which is actually identical to increasing the F_{BL} with 15%.

A.G. Montfoort & F.A. Meijer

The technique developed by Montfoort and Meijer implementing existing data within a company structure is definitely interesting, however not vital in understanding factorial estimation development. An elaboration on the method may be read in appendix I.

Summary: Battery Limit Estimates

It is clear from the previous section that Lang type methods have diverted into various directions. Though the trend from a single Lang factor to factor ranges back to improved Lang factors is also visible in the battery limit estimate techniques: The method of Happel and Jordan[69] is very alike to Peters and Timmerhaus[14]. The fact that merely the sections within the battery limits are assessed leaves questions on how to achieve a full estimates. This is unclear for Bach's[67], Cran's[60] and Montfoort and Meijer's[70] techniques. Another complexity is that the definition of battery limits has changed over time, nowadays mainly containing the process units only.

The adaptation to factors that merely result in battery limit investments do have the potential of improving the accuracy as generally these items correlate better with the equipment costs. The gain in improvement is undone by the relatively rough techniques applied to find costs outside of battery limits, for example explained by Miller[68].

3.2.4 Method Group: Other Lang Type Variants

Methods described in this last section of the Lang type methods do not fit well into the previous categories. Yes, there are similarities, however the discussed methods are different in such an extend that they are now described separately.

J.H. Hirsch & E.M. Glazier

The work published in 1960 by Hirsch and Glazier[71] is a system of equations gradually developed and improved over the years, it led to the set of equations (3.27 to 3.30) presented below for the computation of the total battery limit investment C_{BL}.

$$C_{\mathrm{BL}} = F_{\mathrm{IDC}} \cdot \left[(1 + F_{\mathrm{IL}} + F_{\mathrm{P}} + F_{\mathrm{AM}}) \cdot \sum_{k=1}^{n}(E_{\mathrm{k}}) + \sum_{k=1}^{n}(C_{\mathrm{alloy,k}}) + C_{\mathrm{erected}}\right] \tag{3.27}$$

$$F_{\mathrm{IL}} = 0.635 - \frac{0.992 \cdot hex}{\sum_{k=1}^{n} E_{\mathrm{k}}} + \frac{0.506 \cdot ffv}{\sum_{k=1}^{n} E_{\mathrm{k}}} - 0.154 \cdot \log \frac{\sum_{k=1}^{n} E_{\mathrm{k}}}{1,000,000} \tag{3.28}$$

$$F_{\mathrm{P}} = 0.266 - \frac{0.156 \cdot hex}{\sum_{k=1}^{n} E_{\mathrm{k}}} + \frac{0.556 \cdot pd}{\sum_{k=1}^{n} E_{\mathrm{k}}} - 0.014 \cdot \log \frac{\sum_{k=1}^{n} E_{\mathrm{k}}}{1,000,000} \tag{3.29}$$

$$F_{\mathrm{AM}} = 0.334 + \frac{1.194 \cdot ts}{\sum_{k=1}^{n} E_{\mathrm{k}}} + 0.033 \cdot \log \frac{\sum_{k=1}^{n} E_{\mathrm{k}}}{1,000,000} \tag{3.30}$$

The sum of equipment is determined on a carbon steel F.O.B. price. The basis of carbon steel means that the incremental alloy cost is excluded of E and included as C_{alloy}. Detailed estimates for already installed equipment (for example complex reactors or furnaces) may be included as $C_{erected}$. The factor for indirect costs F_{IDC} is set at 1.4 as a default, containing 15% engineering and supervision, 15% overhead and profit and 10% contingencies.

The last three equations are correlations to determine the factors for installation labour F_{IL}, piping F_P and all the auxiliary other materials F_{AM} such as paint, steel, concrete, etc. These are a function of the equipment mix on non-alloy basis: Total heat exchanger costs *hex*, total field-fabricated vessel cost *ffv*, total pumps including driver costs *pd* and total tower shell costs *ts*.

Reviewing Hirsch & Glazier's Method

This method was revolutionary for the time. In current times the usage of merely formula's instead of visual methods is a normality, in 1960 the use of tables or graphs was the norm. Walas[94] has converted the method into a purely graphical approach.

A second new item is that factors are working on the equipment carbon steel basis price, something that is seen frequently in the Hand type methods. Hirsch and Glazier were the first to implement the effect of alloys on factors into their methods, this was before Miller[68] (chapter 3.2.3) or Clerk[75] (chapter 3.3.1).

Thirdly the determination of factors is dependent on the mix of four equipment types: the fraction of money spent on heat exchangers, field fabricated vessels, tower shells and pumps. Installation labour is positively correlated with field fabricated vessels, which often require cranes to be installed and negatively with heat exchangers. The negative correlation between heat exchangers and piping is puzzling for heat exchanger are associated with piping exactly similar to pumps, which is positively correlated. The inclusion of total plant cost (a function of plants size) is logical, however the log function is questionable: it changes sign around unity and below unity the function is steep, making the method impracticable for small projects.

Data of 42 petrochemical plants was available to calibrate the equations. Therefore one may ask why not every factor was linked to the four fractions, which could improve the accuracy. The usage of this method for other industries is not recommended for the equipment mix types are defining for the petrochemical industry. Reapplying the set of equations on the 42 projects produced estimates ranging between -23% and +38% from the eventual costs, showing decent correlation and applicability for petrochemical plants during that time period.

H.P. Loh, J. Lyons & C.W. White

The method by Loh et al.[72] is relatively modern (2002) and was not intended to be presented as a method on its own. It deduced process equipment prices from ICARUS Process Evaluator a predecessor of the currently popular Aspen Process Economic Analyzer. A more recent (2016) and similar, however less extensive work is done by Symister [38].

$$C_{\text{physical}} = (1 + F_{\text{FO}} + F_{\text{SU}} + F_{\text{B}} + F_{\text{I/L}} + F_{\text{I}} + F_{\text{E}} + F_{\text{P}} + F_{\text{PA}} + F_{\text{M}}) \cdot \sum_{k=1}^{n} (1 + F_{\text{MOC}} + F_{\text{IL}}) \cdot E_{\text{k}} \tag{3.31}$$

The final estimate (eq. 3.31) merely contains the physical cost within battery limits $C_{physical}$, excluding any indirect costs. The system of factors are based on four process types: Solid, solid-gas, liquid-slurry and gas. These categories are then subdivided into process temperature at ± 200 °Celsius (originally 400 °Fahrenheit) and pressure at ± 10 bar (originally 15 psig). The values are included in appendix J, labour and material fractions are applied via equation 3.32. The factors may be collapsed into a single factor value, these are computed and shown in table 3.12. Those may be viewed as a battery limit Lang factor. Smaller factors are found for the high temperature and pressure processes and for solid processes.

$$F_{\text{A,B,C,...}} = M \cdot (1 + L) \tag{3.32}$$

Table 3.12: A merged factor is computed from the values published by Loh et al., see appendix J. The factor converts installed equipment cost into physical cost inside the battery limits.

	Solid		**Solid-Gas**				**Liquid**		**Gas**			
T [°C]	<200	>200	<200	<200	>200	>200	-	-	<200	<200	>200	>200
P [bar]	-	-	<10	>10	<10	>10	<10	>10	<10	>10	<10	>10
Collapsed factor F_{BL}	1.57	1.64	2.00	2.20	2.25	2.34	2.03	2.24	2.25	2.25	2.22	2.32

Reviewing Loh, Lyons & White's Method

The method is unique for it has both Lang type and Hand type characteristics, factors are placed inside and outside the sum. Though it may be argued that it is more a Lang type for when the sum is collapsed, only factors are applied to installed equipment cost, very similar to Aries and Newton[12]. The way factors are determined are very much alike to Happel and Jordan[69] for they have both a material and labour component. Also the categories are similar, except fireproofing is missing and instruments and miscellaneous are added. The value of factors do not deviate much.

The factor's dependency on process type is alike to for example Peters and Timmerhaus[14], to which Loh et al. also refer to if specific modifications are preferred by the estimator. The subdivision based on temperature and pressure is more like Hand type methods that occasional apply pressure or temperature factors. However factors do not vary much among categories. Only the piping costs, a major fraction of the costs, does depend largely on the process type. For solid handling processes a lower value is applied, other variations are small.

It is difficult to directly compare the factors to other factors for the exclusion of indirect costs within a battery limit estimate is unique. If indirect costs are approximated to be 40% of direct costs, then the collapsed factors found are very close to Cran's[60] on page 31.

Summary: Other Lang Type Variants

The two methods placed in this category are considered battery limit estimates. The physical nature of the method by Hirsch and Glazier[71] is vastly different from the methods presented in section 3.2.3. The reliance on the equipment type mix and implementation of factors on a carbon basis are innovative.

The method by Loh et al.[72] is the first to extract data from a software program for publication instead of using published data to construct a program. The method they thereafter present is a mix of Happel and Jordan[69] and Peters and Timmerhaus[14], and only practically employed for battery limit physical costs.

3.2.5 Concluding: General Trends in Lang Type Factorial Techniques

All Lang type estimation techniques have been discussed in previous sections. General trends are visible and reviewed before moving on to the Hand type methods.

- **Art to science**
  After Lang's[59] initiation of the factorial method in 1947 the field generally accepted the method. However it was viewed as a rapid order or magnitude technique and was inferior the estimator's skill, vanguard of these idea's were Chilton[40], Aries and Newton[12] and Miller[68], which employed factor ranges. After the '70's the field was approached in a more scientific manner and estimates were presented as averages, then acknowledged to have a certain degree of error. The best known method was developed by Peters and Timmerhaus[14][89].

- **Graphical to numerical**
  With the introduction of the computer also the focus of data presentation shifted, especially cost curves were ceased to be used. The factorial techniques remain to be published in tables. However Hirsch and Glazier[71] already developed a purely numerical technique in 1960, they were an exception.

- **Lang factor increase**
  The value of the Lang factor has shifted to higher values over time, showing a relatively less expenses made on major equipment pieces. Possible explanations may be the increase of focus on safety, energy savings and instrumentation. A higher Lang factor may induce greater error's for an error in equipment price directly scales with the Lang factor.

- **Diversified Lang factors**
  Distinguishing Lang factors between solid or liquid processes as originally done by Lang remains dubious as shown by Cran[60]. However increased specialisation of Lang factors has the potential to increase accuracy, this is the main reason many authors have shifted focus to diversifying the Lang factors. New categories are for example introduces by Bach[67] correlating it to on geographical locations within plants and Loh et al.[72], who added the gas processes. Montfoort and Meijer[70] introduced calibration of the Lang factor to the company.

- **Statistics**
  An issue with the Lang factors in general is that they are static, the value is determined by the database. Not only were some databases too small to be producing any reliable estimate, most of the data sources are unknown, a positive exception is Bach[67] who published raw data.

- **Industries**
  The type of industry present in the database may be the determining factor for the value of the factors. Since the data source is often unknown the factor may well be not applicable to all market sections. Most (older) databases merely contain petrochemical or chemical projects, excluding accurate estimates for biochemical or food plants. The latter has been resolved by Marouli, Maroulis and Saravacos[65][66]. No specialised factors have been developed for the biochemical industry.

- **The final estimate inclusions**
  However it is tried to be specific on the inclusion of items in this work, the original works often vaguely describe the matter. Most estimation techniques result in a TDC estimate for either green-fields, brown-fields or battery limits investments. Others do not include contingencies, any indirect costs or off-sites. The proliferation of definitions is a serious concern, authors introduce new factors, cancel or merge others, leading to a large variety of categories. This issue is a limiting when comparing factorial estimation techniques.

- **Indirect costs**
  The indirect costs, if included, are a rough estimate and not based on the database. A approximate method was developed by O'Donnell[92] linking indirect costs to direct costs and is considered outdated. However even the more modern popular methods like Happel and Jordan[69] or Peters and Timmerhaus[14][89] apply rules of thumb to account for indirect costs.

- **Equipment cost basis**
  In early cost estimation installed equipment cost as a basis for factors was preferred, for example Lang[59] and Chilton[40]. During that time cost curves for installed costs were available. The increase of cost curve publications on a F.O.B. basis introduced a shift. Either the basis was adapted or factors to convert equipment costs to installed cost provided, for example by Aries and Newton[12], Holland et al.[63] and Loh[72].

3.3 Hand Type

The methods defined as Hand type have factors associated with each equipment piece, rather than a general factor for the sum of equipment pieces. The authors listed in table 3.2 on page 18 are per group elaborated accordingly. Note that these methods are regularly more detailed than Lang methods. It is endeavoured to be clear on the matter without the help of too many words.

3.3.1 Method Group: Original Hand Type Methods

The factorial technique explained in the following section is the method by Hand himself, the founder of the Hand type methods. Very closely related are small adaptations made by Wroth and Clerk, who are also considered to be part of the same group.

W.E. Hand

The 1958 article of Hand[73] has revolutionised the field of factorial cost estimation. The innovation was to assign specialised factors working per equipment type, instead of factors working on the sum of equipment pieces. His formula is shown in equation 3.33, the published factors in table 3.13. The input of equipment cost is an F.O.B. price (rules of thumb are provided in the article), except for furnaces which are on an erected basis. The output is the investment within battery limits. Although the publication of Hand is only one month apart from Bach[67], they have both a totally different definition of battery limits. For Hand only the process units are associated with C_{BL}, identical to Miller's[68] definition.

$$C_{\mathrm{BL}} = \sum_{k=1}^{n} F_{\mathrm{k}} \cdot E_{\mathrm{k}} \tag{3.33}$$

Table 3.13: The installation factors published by Hand[73] in 1958 vary among equipment types, an extended version of the table is included in appendix K.

	Columns	Heat Exchangers	Pressure Vessels	Pumps	Compressors	Furnaces	Instruments	Miscellaneous
F	**4**	**3.5**	**4**	**4**	**2.5**	**2**	**4**	**2.5**

The work of Hand provides the build-up of factors consisting of: Various materials for field construction, field labour and indirect costs. the fabric of factors is split out on these categories is shown in appendix K. Contingencies should be added, according to Hand 10% of total costs is a reasonable figure.

Reviewing Hand's Method

Generally speaking Hand[73] type methods compared to Lang's[59] require the same amount of project definition, though it produces extra work in the estimation procedure for equipment pieces are evaluated individually. The gain is an increase in accuracy for factors are more specialised.

A few issues concerning the method: Hand's factors are only differentiated for 7 equipment types plus a miscellaneous class. The value of 2.5 is on the low side compared to others, the question in what types it is based remains unanswered in the article. To increase usability of Hand's method more factors needed to be developed.

Secondly the database of Lang solely contains petrochemical plants, this is also displayed by the choice of 7 equipment types, which are common in petrol-chemistry. Hand notes that the costs for plants introducing other materials of construction than carbon steel or high pressure equipment should be dealt with in a different way, for it is not contained in his database.

Thirdly the amount plants contained within the statistical database is unknown. The fact that the rounded-off factors were constructed first and only thereafter the field materials and labour components were filled in, is an indication that the factors are a rough estimate only.

The fact that factors are divided into subcategories is useful for the estimator clearly is aware of the highest cost items and may thus increase focus on controlling these costs.

The lowest value is for furnaces, which is logical for it is not based on a F.O.B. price but an erected price, therefore platforms, supports and buildings, equipment handle do not need to be included in the factor. Columns, heat exchangers, pressure vessels and furnaces are assumed to be constructed outside, thus not requiring any buildings. Piping costs are a major part of the final differences observed. Even so are electric costs for electricity consuming equipment pieces like pumps and instruments, however surprisingly not for compressors.

W.F. Wroth

The publication of Wroth[74] in 1960 is merely one page containing table L.1, see appendix L. It contains installation factors similar to those of Hand[73], the equation (3.33) applied is identical. Wroth does provide factor that are more differentiated, however a subdivision as done in table 3.13 is not provided. The installation factor contain: site development, buildings, electrical installations, carpentry, painting, contractor fee's and rentals, foundations, structures, piping, insulation, engineering, overhead and supervision.

Reviewing Wroth's Method

Wroth's[74] factors are an improvement of the Hand method in the sense that the factors are more differentiated. According to Couper[7] these are more accurate than Hand's[73] factors. Wroth has extracted factors from production plants, purchasing department, construction accounting, specificant sheets etc.

Columns, furnaces, compressors, towers and instruments have a similar factor value. This is surprising for furnaces since those were on an erected basis in Hand's method. Wroth's factors for pumps are higher. Because the fractions of field materials, labour components and indirect costs are not tabulated it is hard to find out why the factor is different. It might partly be due to Hand's factors working on equipment including drivers, while Wroth's mostly work on equipment excluding drivers, those are estimated separately, but have a high factor value.

Averagely speaking the items falling in Hand's miscellaneous category, have a higher factor value in Wroth's method. Because of the increased differentiating of that category it is better suited for projects containing man of these miscellaneous items.

J. Clerk

Hirsch and Glazier[71] were the first to indicate tat high alloy usage in construction projects decreases the factor value for auxiliary items and labour. This is true because the increase in equipment cost is faster than for other items. Miller[68] addressed the issue for Lang type methods, he followed the same approach as the work done by Clerk[75] in 1963. Who published a method to implement alloy usage in the Hand[73], which Hand already recognised was an issue.

Clerk's method was based on the ratio of alloy based equipment cost over the carbon steel equipment price. Via six graphs for columns, compressors, heat exchangers, furnaces, pumps and instruments the estimator may determine the installation factor based on the alloy ratio. By initiating way's to incorporate other materials of construction in Hand type estimates is a step forward.

Summary: Original Hand Type Methods

Hand type methods are named to the method introduced by W.E. Hand[73] in 1958, who for the first time applied factor specialised to equipment cost. It led to increased accuracy on estimates at the price of an increase in work effort. Wroth[74] and Clerk[75] both contributed by attempting to improve on Hand's work.

The differences found between the works reveals that a perfect method has not been developed yet. Major issues that are still a concern: The statistical background of data, implementation of indirect costs, resolving differences in factor values between identical equipment types, material of construction implementation and alignment of factor basis are in need of addressing.

3.3.2 Method Group: Separate Instrument Estimates

This group of methods builds on the work of Hand[73] discussed in the previous section. Hand also considered instruments to be individual pieces of equipment, however after Guthrie[78] it was a popular view that instruments were just associated to major equipment pieces. Remember the literature tree, figure 3.1, how methods are organised.

In this chapter the methods are explained that originate from Cran's[60] perspective. Namely that instrument costs do not correlate well with equipment costs.

J. Cran

Cran's[60] 1981 publication is already discussed in the Lang type methods, for he describes new features for both method types in a single article. Cran writes: *"Improvement can only be achieved by reducing the standard deviation and, hence, the variance of the estimating factor."* The improvement in accuracy of cost databases is off less influence because the errors tend to cancel each other out for large projects, small projects are another story.

Four improvements are proposed and thus implemented in the method of Cran:

- Off-sites are estimated separately for they do not correlate well with equipment costs. They may be very different per project and are more dependent on construction environment.
- Instruments are included separately for they also do not correlate well with equipment costs. The amount of instruments is based on process conditions and company regulations.
- Specialised factors (Hand type) have the preference above singular factors (Lang type).
- Indirect costs are a function of total direct costs instead of a function of equipment costs.

Cran's method is characterised by equations 3.34 to 3.36. The first equation relates the total direct major equipment cost $E_{T,direct}$ to F.O.B. prices of equipment associated with a equipment specific factor F. The second formula shows the separate estimate for instruments' direct costs $I_{T,direct}$ gained with a single instrument factor F_I and instrument F.O.B. cost I.

$$E_{\mathrm{T,direct}} = \sum_{k=1}^{n} F_{\mathrm{k}} \cdot E_{\mathrm{k}} \tag{3.34}$$

$$I_{\mathrm{T,direct}} = F_{\mathrm{I}} \cdot \sum_{i=1}^{n} I_{\mathrm{i}} \tag{3.35}$$

$$C_{\mathrm{BL}} = (E_{\mathrm{T}} + I_{\mathrm{T}}) \cdot (1 + F_{\mathrm{indirect}}) \tag{3.36}$$

The direct cost factors are shown in table M.1 in appendix M, accounting for all secondary materials (except instruments) and are material of construction specific. The factor for indirect costs $F_{indirect}$ is only a rough estimate, Cran cites O'Donnell[92], making indirect costs a function of direct costs, like other authors that did not provide any reasonable indirect cost estimation procedure.

Reviewing Cran's Method

The four points of improvement by Cran[60] are valid. However there is always a trade off between accuracy and amount of work. Cost information on instruments is relatively difficult to find, for other methods include them within the factored estimates. Cran refers to Roberson[95] and Stogens[96] as available resources during that time period. The addition of Liptak's[97] and Woods's[44] database, the latter including separate instrument costs in 2007 relaxes the problem. The increase in detailed engineering necessarily for estimating off-sites and instruments in particular do not increase the accuracy a lot, because the dollar values are relatively small. The estimation technique of O'Donnell[92], is approximate and aged, and this may well frustrate the aim for higher accuracy.

Employing specialised factors per construction alloy does not significantly increase the work compared to other Hand type methods. The way of presenting is similar to Wroth[74], not giving any information on the subdivision into materials and labour. The standard deviation on all Cran's factors may be taken as approximately 15%, this number is useful for the determination of the estimate's accuracy. Because he had access to more than 90 chemical plant construction projects, this number is reasonably reliable for the common types of equipment.

The listing of factors for various alloys is also an improvement compared to Hand's[73] or Wroth's[74] methods. However a list is limiting in the fact that it is never complete, how to cope with this is included in the method of Brown[76][77] in the next section.

The value of Hand's and Wroth's factors may be compared to Cran's by reducing the factors by a fourth to eliminate the indirect costs, which are also not present in Cran's factors.

Cran's factors seem to be lower at first glance, however one may only compare the factors based on basic materials (carbon steel), making the comparison very limited. Comparing the adjusted factors Cran's are on average still 15% lower in value than Wroth's. Possible explanations for the differences are the difference in time (20 years) or in the database such as types of processes, locations, projects, environment, etc.

T.R. Brown

Brown's first method was published in a short article[76] in 2000 and the inclusion of building estimates and other adaptations in a 2007 book[77].

The Brown method exists of an adapted version Hand type methods. Correction factors for alloy usage, plants environment and the need of building complexes are introduced, see equation 3.37. The TDC is a function of the sum of F.O.B. priced equipment associated with a Hand type factor F_H (original value[73] or from Garrett[81]). The alloy correction factor f_{MOC} corrects the original Hand factor, that is based on carbon steel construction, to other materials of construction. This is similar to the ideas of Clerk[75], however in Brown's work it is a general relation and not equipment dependent. On the y-axis of figure 3.4 is the correction factor, the x-axis displays alloy-ratio AR, which is the relative price between the used alloy and carbon steel. A fourth-order polynomial is fitted trough extracted data points of the curve, leading to equation 3.38, strictly applicable over the shown range (1 - 7.5).

$$C_{\text{TDC}} = F_{\text{I}} \cdot F_{\text{B}} \cdot \sum_{k=1}^{n} (F_{\text{H,k}} \cdot f_{\text{MOC,k}} \cdot E_{\text{k}}) \tag{3.37}$$

$$f_{\text{MOC}} = 0.00136 \cdot AR^4 - 0.0278 \cdot AR^3 + 0.2112 \cdot AR^2 - 0.7374 \cdot AR + 1.5272 \tag{3.38}$$

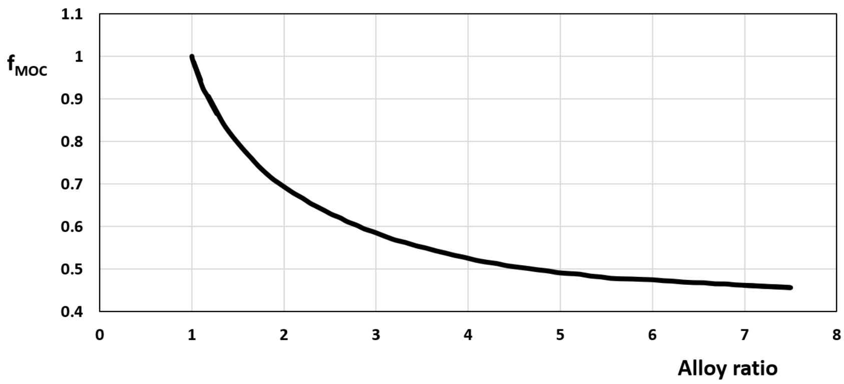

Figure 3.4: The alloy correction factor extracted and replotted from Brown[76].

The building F_B and instrumentation F_I factors are based on the works of Peters and Timmerhaus[14] and Garrett[81] respectively. The values are tabulated in appendix N. The building factor is a function of type of process (solid/liquid) and type of project (new/expansion). The instrumentation factor is necessary to apply since Hand's or Garret's factors do not include instrumentation costs.

Reviewing Brown's Method

The method explained by Brown[76][77] is a tangle of aspects from other methods. The core of the method is by Hand[73] and it is questionable to still employ those factors for their age and statistical background in the petrochemical industry. Brown defends by stating that other factors only deviate approximately 20%. The implementation of the alloy correction factor is useful for this was missing in Hand's method. It was partially solved by Cran[60], but Brown's idea based on Clerk[75] is applicable in any situation for it is universal.

The factor for control based on Garrett[81] is of a low accuracy. Although the inclusion of instruments remain a concern, this is not the way to solve it. The ranges are broad (35%) and based on little information, leading to large differences in the final estimates without proper argumentation.

The building factor of Peters and Timmerhaus[14] is a better idea, for the scheme to choose from is clear, consequentially the numbers are explainable.

The original publication of Brown also adds a factor correcting for the plant's geographical location. Although locations are an important factor to take it into account, it is left out of this review. Location factors are discussed in chapter 3.4.2.

D.R. Woods

Woods'[44] book provides the Chemical Engineer with a vast database on cost estimation, both for equipment estimates and factors associated with each piece. Woods states that the numbers are only ballpark figures, accurate up to +/-30%.

$$C_{\text{BL-L\&M}} = C_{\text{I}} + C_{\text{B}} + \sum_{k=1}^{n} (F_{\text{L\&M*,k}} \cdot f_{\text{MOC,k}} \cdot E_{\text{k}}) \quad (3.39)$$

$$C_{\text{BL-PM}} = C_{\text{BL-L\&M}} + C_{\text{TFI}} \quad (3.40)$$

$$C_{\text{BM}} = C_{\text{BL-PM}} + C_{\text{O}} + C_{\text{E\&C}} \quad (3.41)$$

$$C_{\text{TM}} = C_{\text{CF}} + C_{\text{C1}} + C_{\text{C2}} \quad (3.42)$$

Equations 3.39 to 3.42 display Woods' estimation scheme. The terminology is similar to Guthrie's (modular), explained in the next chapter. The first two equations refer to costs within battery limits (BL) only, which is defined as anything within 1 meter of the process equipment boundary. Each equipment piece is corrected by Brown's[76][77] alloy factor f_{MOC} (see previous chapter) and multiplied with the factor F_{L+M*} accounting for direct material and labour costs, e.g. foundations, structures, installation, paint, etc. The factor, in contrast to most other methods, does not include (within battery limit) buildings costs C_B and instrumentation costs C_I. The * is a reminder for that fact. Woods' database also contains cost estimates for common instruments, however no method to assess buildings costs is included. The various other costs made within projects are estimated approximately, as depicted in table 3.14. No method is provided to account for off-site costs C_O.

Table 3.14: The rough rule of thumb estimation numbers for indirect costs in Woods'[44] estimation method.

Cost item	% of	**....**
Taxes, freight, insurance (TFI)	15 - 25	F.O.B. sum
Engineering and construction (E&C)	10 - 45	$C_{L\&M}$
Contractor fee's (CF)	3 - 5	$C_{BL\text{-}BM}$
Contingencies for delays (C1)	10 - 15	$C_{BL\text{-}BM}$
Contingencies for scope changes (C2)	10 - 30	$C_{BL\text{-}BM}$

Reviewing Woods' Method

The value added by Woods is found in the extensive database, which is the largest available in literature in terms of equipment types. Woods provides the estimator with separate estimates (mostly F.O.B. prices) for multiple equipment set ups having the same overall function. For example crystallisers are divided into batch, forced circulation, draft tube, CPR, scraped surface and triple effect forced circulation. Also alloy correction factors for multiple materials are given per type of equipment, which does increase the accuracy.

The method may therefore also be fitted into the group of 'Modern databases' discussed in chapter 3.3.6. However the way the data is presented by Woods is traditional and based on Williams'[21] sixth-tenth rule, namely with a base price at a base capacity and an exponent value applicable to a certain range. Woods provides multiple relations based on appropriate capacities units (size, flow, etc.) for the same equipment piece, letting the estimator choose on availability of information, which is convenient. The fact that each equipment type comes with associated F_{L+M^*} values, makes it relatively easy to find the installed costs without having to cross-reference it with other databases. It does occur that the factors are provided in a range, the lacking of proper guidance makes it difficult for the estimator to choose the correct value.

To find the final estimate of total module cost the factors of table 3.14 are applied. All are presented as a range giving an idea on ballpark numbers, however not providing any method to come to a more detailed accurate estimate. Considering the amount of work necessary to perform the battery limit estimate, it is unfortunate to cancel the accuracy gain in that part by rough approximation in later stages.

J.R. Couper, W.R. Penney, J.R. Fair & S.M. Walas

Couper et al.[47] published a book chapter on cost of equipment in 2012. The price data is solely based on previously published databases from the 70's onward, of which Peters and Timmerhaus[89] (2003) and Ulrich and Vasudevan[98] (2007) are the most recent. The F.O.B. cost relations are mostly given as a series of logarithmic function dependent on a capacity parameter, then adjusted by factors for pressure, materials of construction, subtype (for example plate and frame or shell and tube heat exchanger).

The factors employed are those from Cran[60], page 123. Instrumentation is not included in these factors, however the database of Couper et al. do not include prices for instruments and are not clear on that perspective or on the factor estimate procedure at all. The presumed accuracy is within 25% error, a lower number may not be expected for the inclusion of old databases.

Summary: Separate Instrument Estimates

Uncoupling the instruments dollars from equipment cost does improve the estimate accuracy if done properly as done by Cran[60] and Woods[44]. However the accuracy gain is low for the relative dollar value of instruments is low compared to other cost items.

If the scope of a project is not well defined yet, the instrumentation may well not be determined leading to potential accuracy decrease due to poor estimate choices. The increase in engineering work performed, while the gain in accuracy is questionable, may be reason not to estimate instruments separately.

The methods contained within this group have been popular and well defined, therefore all methods in this category remain workable. The introduction of Brown's[76][77] alloy correction factor is universal and the databases of Woods[44] and Couper et al.[47] modern and extensive.

3.3.3 Method Group: Guthrie Type Methods

The methods contained in the Guthrie method group have been cited numerously and have been considered best practise from 1970 up to the 21$^{\text{th}}$ century. The methods developed from the early work of Guthrie, thereafter small improvements took place. The modular concept though is both detailed and work-intensive.

K.M. Guthrie

In 1969 Guthrie published an article[78] changing the concept of Hand type cost estimation. Small improvements, more extensive explanations and increased data on costs were added in a 1974 book[79].

The main conceptual change was to allocate six modules, which became five (merged fluid and solid handling) in the later work:

- **Chemical Process Module C_{CP}:** Contains cost for all major equipment items including secondary materials and labour. In other methods this would be considered the physical battery limit investment.
- **Building and Structures Module C_B:** Contains costs for steel structures for process equipment and auxiliary service buildings including cafeteria, laboratory, HQ, etc.
- **Off-site Facilities Module C_O:** Contains costs for all supporting activities, such as utilities, storage facilities, and distribution systems outside battery limits.
- **Site Development Module C_Y:** Contains costs for yard improvements, examples are drainage, fencing, fire protection, landscaping, piling, paving, parking lots, excavation, etc.
- **Project Indirect Module $C_{indirect}$:** Contains costs for construction overhead, engineering and home office, contingencies and contractor fee's.

The total depreciable investment C_{TDC}, called totale module (TM) cost by Guthrie, may be computed by summing the five modules. Regularly however the value of the indirect module is computed via a factor, like equation 3.43.

$$C_{\text{TDC}} \;=\; (C_{\text{CP}} + C_{\text{B}} + C_{\text{O}} + C_{\text{Y}}) \;\cdot\; F_{\text{indirect}} \tag{3.43}$$

Each category is than elaborated, the centre role is still played by the chemical process equipment. Adjustment factors working on F.O.B. equipment prices for sub-design type of equipment f_D, pressures f_P, materials of construction f_{MOC}, etc. Factors are available to convert F.O.B. price E to each secondary labour component M (piping, concrete, steel, instruments, electrical, insulation and piant) and the labour component L. It is most convenient to use averages, however each material components is adaptive based on equipment type and total equipment dollar value and the labour components are read out of a curve based on each material component dollar value. If required the estimation process may so be very detailed.
The eventual estimate (equation 3.44) for the process module then contains the equipment F.O.B. cost, secondary materials cost and labour cost. This is called (M&L) level and may be used in the sum of equation 3.43.

$$C_{\text{CP}} \;=\; \sum_{k=1}^{n} (F_{\text{M,k}} + F_{\text{L,k}} + f_{\text{D,k}} + f_{\text{P,k}} + f_{\text{MOC,k}} + ...) \;\cdot\; E_{\text{k}} \tag{3.44}$$

The assessment of the other categories, C_B, C_O and C_Y, are detailed and require a significant project definition. A more elaborate explanation / discussion is found in appendix O. A table showing the values of Guthrie's installation factors, and a discussion on indirect costs is also found there.

Reviewing Guthrie's Method

The method devised by Guthrie[78][79] is moving away from the classical factorial methods and adopts characteristics of more detailed estimation techniques. Therefore the space in this work does not allow it to fully explain the method. A high accuracy is attributed to the method, however the amount of work and project definition requirements are also high. The estimate for battery limit (and some off-sites) investments is equally easy to perform as other methods. However is the estimator is willing, all factors may be adapted to the circumstances, increasing accuracy but also effort. To come to a full estimate of costs including site development, piping and buildings a realistic plan should already be on the table. These considerations make Guthrie's method less usable for rapid estimation or scanning of alternatives.

The cost database is quite extensive and has been incorporated in many other databases by later authors.

The cost structure of Guthrie for process equipment is flexible for every adaptation in subtype, pressure, model, alloy, or any other parameter may be captured in the addition of a factor, making these estimates very specialised. The module installation factor does not change for it works on the basis equipment carbon steel price. This is definitely a large advantage of summarising the cost data in this manner.

The value of the factors (appendix O are compared to Hand's[73]. Different is the inclusion of instruments in the factors. If these are extracted from Guthrie's the total module factor decreases by 0.02 for compressors to 0.16 for vertical process vessels. As a rule of thumb this is a decrease of 1% - 4%. This also the relatively low value (in the '70's), and makes one doubt the increase gained to estimate it separately as done by Cran[60], Brown[76][77] and Woods[44]. The factors of Hand and Wroth include buildings, however these are also relatively a small value. lowering the factor for pumps and compressors by 5% and 10% respectively.

When the factors are adjusted and compared the differences in factor value between Hand and Guthrie is always less than 20%, Hand's values are generally higher. The ratio's between labour and materials for both methods is very similar for all equipment types, a difference is that the indirect costs in Guthrie's factors are a relatively larger cost item. The similarities in values is not surprisingly for both methods were developed based upon U.S.A.'s petrochemical industry.

Compared the Wroth[74], Guthrie's factors are also lower. On average the comparable values are approximately 30-40% higher in Wroth method. Especially pumps are rated higher in Wroth's factors, approximately by a factor two. The reason for this is unknown. Significant differences between Wroth and Guthrie are expected to be observed.

G.D. Ulrich

The book by Ulrich[80] written in 1984, is mainly targeting students as an audience. The book is advocating the use of Guthrie[79]. It does contain cost curves mostly based on Guthrie, however there are a few useful additions such as water treatment plants, steam generators and flares.

The estimation of site development $C_{Y\text{-}TM}$, off-sites $C_{O\text{-}TM}$ and buildings $C_{B\text{-}TM}$ at total module level (including all direct and indirects also contingencies), was very detailed in Guthrie's method. A solution by Ulrich, extracted from Guthrie's numbers, is presented in table 3.15, which gives a short-cut method. This leads to equation 3.45, in which the chemical process module cost $C_{CP\text{-}TM}$ is similarly calculated as in Guthrie's method.

$$C_{\text{TDC}} = C_{\text{CP-TM}} \cdot (1 + F_{\text{Y}} + F_{\text{B}} + F_{\text{O}}) \qquad (3.45)$$

A second innovation is presented by Ulrich, a more dissociated way of assessing costs for implementing costs for alloy's. It is a correction factor working on the bare module costs taking into account what fraction of piping is replaced by alloys. That adaptation is not shown here for it is tedious and out of scope for this report.

Table 3.15: The estimation of other modules than the chemical process module (battery limits), may be estimated by the shown numbers of Ulrich[80].

Cost item	Factors values
Site development F_Y	0.04 - 0.06
Buildings F_B	0.02 - 0.06
Off-site facilities F_O	0.17 - 0.25

The table employed by Ulrich[80] to asses costs outside of battery limits is useful for now the estimator may choose to get an approximate or detailed estimate based on schedule, availability of plot plans and requirements for decision making.

D.E. Garrett

The method employed by Garrett[81] is virtually identical to the battery limit, chemical process, estimation module of Guthrie[78][79]. Therefore those equations apply. The module factor values, tabulated in table P.1 in appendix P, are published by Garrett to replace Guthrie's factors. Only these include all secondary equipment, installation labour and project indirects costs excluding contractor fee's and contingencies.

The book was published in 1989, and this is visible in the factors available for the type of equipments: Ion-exchange methods, dust collectors and vacuum equipment are introduced. In the work cost curves are provided for any equipment category that also has a factor associated.

Although instruments are already part of the estimate, a control philosophy correction is added by Garrett, adopted from Liptak[97]. In modern ages plants may be subject to increased automation, apparently not captured within his factors. The control philosophy factors are given in table P.2 on page 128.

Reviewing Garrett's Method

According to Brown[76], estimates made with Garrett's[81] factors only abbreviate 3,5% from estimates with Hand's[73] method, this is surprising for Hand only published 7 factors plus one for miscellaneous items, and the amount of years in between the two publications is significant. On the other hand it is in line with the conclusions of previous chapter on Guthrie[78][79], showing that Guthrie's factor are approximately 20% lower than Hand's, while Garrett's factors are again higher than Guthrie's. This confirms the close similarity of the factor databases. Although Garrett did not provide information on the origin of the data it is likely to be the petrochemical industry or partly straight from Hand and Guthrie.

The inclusion of the instrumentation correction factor is optional and should be used with caution if implemented in contemporary estimates. The numbers are already 40 years old and may not reflect today's control philosophies. The extra work added may also not add up to the accuracy gain, similarly to the methods in the other category that have increased focus on instruments. An auxiliary downside is the fact that Garrett's factors do not seperately show secondary item cost such as instruments.

Summary: Guthrie Type Methods

The popular Guthrie[78][79] method is claimed to be accurate, however the amount of required preparation effort is high. It can also be successfully applied to find grass-root plant estimates based on plot plans, whereas other methods revert to approximate numbers. Ulrich[80] filled this gap by providing approximate values directly applicable in Guthrie's method. Garrett[81] provided updated factors, however his method is without adaptations (for example Ulrich's) merely applicable to battery limit investments.

The values of Guthrie's factors were found to be lower than Hand's[73] and significantly lower than Wroth's[74]. Garrett's factors were very similar to Hand's values, only more specified to 58 different factors.

3.3.4 Method Group: Labour Focussed

The word 'group' does not apply here, since merely a single method is discussed in the following section. It has large similarities with other methods, however it intensives labour cost assessment.

I.V. Klumpar & S.T. Slavsky

However Klumpar & Slavsky's[82][83][84][85] method is interesting in the way it handles labour costs, it is not included here. The method has had little influence on later cost estimation literature, therefore it is discussed in appendix Q. It was found that factor values differ significantly from other methods. A second conclusion is that the increased focus on labour may especially be beneficial when construction takes place on locations other than the U.S.A.

3.3.5 Method Group: The IChemE Method

The method's group name is derived from the Institution of Chemical Engineers (IChemE) and is elaborated in the following section.

A.M. Gerrard, D.J. Brennan & K.A. Golonka

The institute endorsed this estimation technique by publishing it in both a book written by Gerrard[15] (2000) and a paper by Brennan and Golonka[86] (2002). The two are identical in factorial application. Their main observation is that there is more variability in factors due to equipment type than equipment dollar value. Consequently it is concluded that it is more accurate to discriminate factors based upon equipment price rather than type.

The IChemE technique shows similarities with Miller[68]. His Lang type estimation method is cast into a Hand type to deliver the new factorial technique, shown in equations 3.46 and 3.47 (see page 75 for nomenclature). The factors (except piping) are applied on the purchase price of carbon steel (CS) equipment. This delivers direct plant cost C_{DPC}, adding indirect costs provides total battery limit cost C_{BL}.

$$C_{\text{DPC}} = \sum_{k=1}^{n} E_{\text{k}} \cdot (1 + F_{\text{P,k}}) + E_{\text{CS,k}} \cdot (F_{\text{IL,k}} + F_{\text{I,k}} + F_{\text{E,k}} + F_{\text{B,k}} + F_{\text{CV,k}} + F_{\text{I/L,k}}) \quad (3.46)$$

$$C_{\text{BL}} = (1 + F_{\text{E\&S=15\%}} + F_{\text{MO=10\%}} + F_{\text{C=10-20\%}} + F_{\text{CF=5\%}}) \cdot C_{\text{DPC}} \quad (3.47)$$

Table 3.16: An example of determining factors (buildings) by Gerrard[15] and Brennan and Golonka[86]. The prices are given in 2000 pound Sterling per equipment piece.

Consideration	**Factor value per piece £ (2000) range** Over 300,000	100,000 to 300,000	40,000 to 100,000	20,000 to 40,000	6,000 to 20,000	3,000 to 6,000	Under 3,000
- Negligible structural work and buildings	0.012	0.025	0.025	0.04	0.05	0.06	0.08
- Open air plant at ground level with some pipe bridges and minor buildings	0.06	0.08	0.1	0.14	0.17	0.21	0.26
- Open air plant within a structure	0.14	0.24	0.31	0.41	0.05	0.59	0.74
- Plant in a simple covered building	0.19	0.29	0.39	0.48	0.56	0.69	0.85
- Plant in an elaborate building on a major structure within a building	0.35	0.48	0.63	0.76	0.9	1.06	1.38

All factors are a function of equipment piece value in 2000 £Sterling and auxiliary considerations. An example is given in table 3.16; the scheme for the building factor F_B. It contains hints on how to choose the correct factor, the scheme is merely a guideline and be adapted if the estimator feels it is necessary. On the contrary an average value may be applied if not enough information is available to choose between considerations.

Reviewing Gerrard, Brennan & Golonka's Method

The basis of the IChemE method is British in contrast to other methods, which are all developed in the U.S. The position that secondary materials and labour correlate better with equipment price instead of type is discussed and assumed to be true by Brennan and Golonka[86], however not proven. It is interesting to investigate it since it is the basis of the IChemE method.

The scheme of determining the correct factors for each type is mimicked from Miller's[68] method, which employs roughly the same cost categories. A difference is that Miller is based on the average equipment cost (Lang type). Secondly Miller provides more detailed estimate techniques for off-sites. The IChemE method initially published by Gerrard[15] is not very clear on it's inclusions. The factors are developed on basis of brownfield/extension projects and are best used for that purpose. Green field projects are not discussed. Brennan and Golonka discuss revamp projects, for which the IChemE method shows poor results. This is due to the fact that modifications require relatively more indirect costs and are often associated to increasing process control thus relatively high instrumentation costs not represented by the factors.

The conversion of equipment constructed from alloy equipment to a carbon steel basis is executed applying alloy factors. No new factors are given by the authors, so they should be extracted from existing literature. For example Brown[76][77] has published a universal method to do so. Or equipment type specific factors may be found in Guthrie's[78][79] database. These correction factors are published as a single number, while Brennan and Golonka note that the factor correlates with equipment size, namely the contribution of alloy material compared to other materials and labour.

3.3.6 Method Group: Modern Databases

The modern database group is not characterised by the factorial methods they employ, but by the way the present cost databases. Historically these have always been displayed in cost curves based on the sixth-tenth rule of Williams[21]. The sources presented in the following subsection are developed after the introduction of computers and are not necessarily correlated via the sixth-tenth rule, but may follow any trend closest fitted to the data.

A. Chauval, G. Fournier & C. Raimbault

The method proposed by Chauvel et al.[61] (2003) (first published in 1975) is developed by the company Technip and based on their available data. The base of the presented data is the year 2000 in euro €. The equipment database and method is claimed to be versatile and applicable for both large scale companies possessing detailed data and estimators having less sophisticated data available.

The published factors account for auxiliary costs for installation labour, piping and valves, civil work, steel structures, instrumentation, electrical equipment, insulation, painting and all indirect costs. Thus it is essentially similar to the total module factor of Guthrie[78][79], only the base for Chauvel's method is ex-factory (purchase) price. The value of the factors, see table R.1 in appendix R, are developed in-house and are split into the cost items for furnaces, pumps, compressors, heat exchangers and pressure vessels. Other factors, which include some off-site facilities, are merely provided as the total factors. The way of determining the investment, equation 3.48, is straightforward. The battery limit investment BL is in this definition also including utilities and storage, which are estimated similarly to the process units.

$$C_{\mathrm{BL}} = \sum_{k=1}^{n} E_{\mathrm{k}} \cdot (F_{\mathrm{k}} + f_{1,\mathrm{k}} \cdot f_{2,\mathrm{k}} \cdot f_{3,\mathrm{k}} \cdot f_{\ldots,\mathrm{k}}) \tag{3.48}$$

The factor F in equation 3.48 is applied on the base price, just like all the correction factors f. These correction factors may be applied in a specific structure depending on the equipment piece.

Reviewing Chauval, Fournier & Raimbault's Method

The claim that the method is flexible is puzzling for the required input and way of estimating is similar to Guthrie[78][79]. That the origin of the method lies in Europe is an advantage for the European market: Most methods originate from America, while accurate conversion is hard. The choice to use ex-factory price instead of F.O.B. prices is a disadvantage for the method is less useful in implementing alternative equipment cost databases.

The addition of utilities and storage inside the battery limit costs may be confusing when comparing the results of various methods. Some considerations are shared by Chauval et al.[61] how to adapt to assessing a food plant or other plants using alloy piping; Adjusting of factor values of piping in the principal equipment section is necessary. Another valid note is that piling would seriously increase the civil work costs.

The factor value of more specialised equipment is lower than for principal equipment, this trend is also visible in Hand[73], Guthrie[78][79] and other associated methods. The reason for this is, as posed by Chauval et al., is that special equipment often contains more moving parts and more attention is paid in preparing it before installation at site.

The value of Chauval et al.'s factors is generally low; on average lower than Guthrie's which are considered low compared to Hand's[73] and Garrett's[81]. Only factors for compressors, air cooled heat exchangers, storage tanks and furnaces are represented by a relatively high factor value. There may be several reasons for this difference: The database of Chauval et al. is based on European prices, giving rise to differences in equipment price to secondary items or labour ratio's compared to American databases. Secondly the time of factor determination is decades later than those named previously also provoking change in these ratio's. A third reason may be the nature of the 'base price', Chauval et al. employ a different set of correction factors. The working of the factors on ex-factory price rather than F.O.B. price, including freight, sales tax and insurance into the indirect cost item, should have the opposite effect: Higher factors.

W.D. Seider, J.D. Seader, D.R. Lewin & S. Widagdo

The book by Seider et al.[17] is equipped for educational purposes. The factorial techniques presented in the book (3^{th} edition - 2009) are from Lang[59], Hand[73] or Guthrie[78][79]. Progress is found in the cost data. Thankfully the authors are an exemption and provide the sources of their cost data, which were collected from 13 publications in the period from 1949 to 2003. It is astonishing to discover it is necessary to incorporate aged data to compose an adequate database.

The database provided to the reader is well described and clear on the inclusions. The F.O.B. prices are described with equations, these may be linear, exponential, or any other fitted line.

R. Sinnott & G. Towler

The cost database in Sinnott and Towler[46] is relatively new (consulted the 2012 version) and based on previously discussed literature and online sources. The cost data is presented in sixth-tenth rule type of equation, an exponential behaviour as seen in formula 3.49. The size parameter is equipment type specific and may for example be volume, flow, area, etc., The exponent n, and other fitting parameters K_1 and K_2 are tabulated per equipment type accordingly.

$$E = K_1 + K_2 \cdot S^{\mathrm{n}} \tag{3.49}$$

The factorial methods endorsed are Hand's[73] or Peters and Timmerhaus'[14] which is a Lang type method. However the numbers employed are higher than those originally proposed by Peters and Timmerhaus (see page 23).

R. Turton, R.C. Bailie, W.B. Whiting & J.A. Shaeiwitz

The cost database of Turton et al.[45] (3^{rd} edition from 2008) is principally based on the work of Guthrie[78][79], Ulrich[80] and partially on Richardson's R-Books. The database is designed to be incorporated within a capital cost estimation software tool, see chapter 3.5. The cost relations for ambient pressures and carbon steel are all fitted to the type of equation 3.50, in which K_1, K_2 and K_3 are constants specific to the type of equipment and S is the size parameter (flow, volume, etc.). The database is extensive with 95 equipment types.

$$\log_{10} E = K_1 + K_2 \cdot \log_{10} S + K_3 \cdot (\log_{10} S)^2 \tag{3.50}$$

Pressure factors fitted from Guthrie's data are correlated via the same type of equation as (3.50). Three new constants relate the pressure to a pressure correction factor f_P. Accounting for materials of construction is done with static material correction factors f_{MOC} tabulated for 40 equipment constructions, these also incorporate data from Perry et al.[19], Peters and Timmerhaus[14] and Navarette and Cole[25].

$$F_{\mathrm{BM}} = K_{\mathrm{a}} + K_{\mathrm{b}} \cdot f_{\mathrm{MOC}} \cdot f_{\mathrm{P}} \tag{3.51}$$

The factorial technique is copied from Guthrie and Ulrich, and is condensed to show the bare module factors only, these convert F.O.B. costs of equipment to battery limit TDC investment excluding factors for contingencies F_C and contractor's fees F_{CF}. These may be taken as 18% of bare module cost, this is equal to the average value given by Guthrie. The overall factors for heat exchangers, process vessels and pumps are calculated via equation 3.51, again applying constants. For other equipment types the correction factors are simply multiplied with tabulated module factors. Equation 3.52 is employed to compute the total investment within battery limits.

$$C_{\mathrm{BL}} = (1 + F_{\mathrm{C}} + F_{\mathrm{CF}}) \cdot \sum_{k=1}^{n} F_{\mathrm{BM,k}} \cdot E_{\mathrm{k}} \tag{3.52}$$

Reviewing Turton, Bailie, Whiting & Shaeiwitz' Method

The data embedded in the database of Turton et al.[45] has been extracted from Guthrie[78][79] and Ulrich[80]. Examples are being worked out in appendix C and compared in chapter 4.1. The transfer of data from the older sources to algorithms is much better suited to contemporary needs and applications.

The factored method employed merely includes battery limit estimates. Turton et al. note that for grass-root plants 20% to 100% more investment is associated with an average of 50% extra costs. This estimate is based on a review of Miller's[68] work, which was published more than 40 years before the analysis.

Summary: Modern Databases

The latest discussed group contains recently published methods. All employ factors closely related to the method of Guthrie[78][79]. Chauval et al.[61] have published in-house developed factors based for the West European market, which are generally lower than others. The other methods by Seider et al.[17], Sinnott and Towler[46] and Turton et al.[45] however have merged older factors mainly those from Guthrie.

3.3.7 Concluding: General Trends in Hand Type Factorial Techniques

The previously discussed Hand type factorial estimate techniques are now summarised by identifying the key trends within the literature.

- **Specialising to equipment types**
  Hand's[73] publication contained seven equipment specific factors plus one extra for all miscellaneous types. Later authors responded by adding factors more specialised to equipment types or subtypes. Examples are Wroth's[74], Guthrie's[78][79] or Chauval et al.'s[61] factors, those being similar in structure to Hand's.
- **Cost items carved out of factors**
  According to Cran[60] the correlation between instruments and equipment value is poor. He introduced factors which do not account for instrument material and their installation labour, which was a regular procedure before that time. Brown[76][77], Woods[44] and Couper et al.[47] followed up on this idea. This division is the largest chasm across Hand type methods. Another split is the increased focus on labour costs by Klumpar and Slavsky[82][83][84][85], which are intended to slow down the ageing of factors and make it easier to pin down effects of geographical location choices. However for both these methods the gain in accuracy is generally low compared to the increase in effort: Instrumentation design choices or labour wages and productivity per profession are to be found by the estimator before the estimate can be performed. The increase in accuracy is expected to be low for the money value of especially instruments compared to the total money sum is low.
- **In and outside battery limits**
  Most Hand type factorial techniques appear best suited for estimates within battery limits. Off-sites are generally not estimated, because as Cran[60] noted: Those do not correlate well with equipment costs. An exemption is the work of Brown[76][77] that employs a building factor which differs for new plants versus extensions. Guthrie's[78][79] modules are the only viable method to estimate off-site costs in detail. However the process is tedious and requires detailed design information. In most cases these are simply not yet present during class 3 or 4 (see chapter 2.1.1) estimation work. Ulrich[80] extracted rough estimate

numbers from Guthrie's data to account for buildings, site development and facilities. Guthrie[78][79], Ulrich[80], Garrett[81] and Chauval et al.[61] compute costs for utilities and storage in the same manner as process units within battery limits.

- **Indirect costs**
  The costs for all indirect cost items are sometimes incorporated within the total factor. However when this is not the case, see Woods[44], Gerrard[15], Brennan and Golonka[86] and Klumpar and Slavsky[82][83][84][85], the numbers are only rules of thumb. This is curious for a large effort is put into estimating the direct costs, while the indirect costs are often a large fraction of the total money sum and equally important to accurately perform estimations. The gap is probably existent because of the lack of reliable estimation techniques for indirect costs. The same conclusion was made for Lang type methods.

- **Secondary materials and labour**
  The methods by Hand[73], Guthrie[78][79] and Klumpar and Slavsky[82][83][84][85] showed the break down of factors into secondary materials and labour. Starting with Wroth[74] and the majority of modern methods do not discriminate, but only present the total factor. The reason why is unknown, the fact remains that the amount of information to the estimator is now more limited.

- **Data recycling**
  The contemporary methods have incorporated a limited amount new datapoints into their databases, and when done so it is often not clear what data was used. Consequentially applying certain methods being based on older data, or certain industries may harm the estimation's accuracy if applied to other industries. The lack of referencing data for both equipment cost databases and factor values is a serious problem, diagnosing factorial techniques without case study testing is only possible to a limited extend.

- **Factor values**
  It is hard to compare the values of factors for some work on a different basis. Some equipment items are more common in certain fields, leading to various scenario's for the final estimates. On average the factors presented by the group seperately estimating instruments and direct costs like Cran[60] and Woods[44] are lower than others. The factors by Chauval et al.[61] are generally low, possible explanations is the basis of data within Europe rather than America. A little higher are Guthrie's[78][79] factors followed by Hand's[73] and Garrett's[81]. Brown[76][77] claimed that the results after applying the latter two is virtually identical.

- **Cost curves**
  The more recent equipment databases are presented by numerical relations rather than graphical methods, this is depicted by the modern database group. This trend is logical for the increase in computer usage make it a more viable format. Examples are the databases by Seider et al.[17], Turton et al.[45] and Sinnott and Towler[46].

- **Correction factors**
  The amount of employed correction factors increased through time. Where Hand's factors only apply to carbon steel low pressure plants, contemporary methods (like Chauvel et al.[61], Turton et al.[45], Guthrie[78][79] or Woods[44]) employ factors to account for subtypes, pressures, temperatures, alloy's or other parameters related to the equipment piece. The most versatile alloy correction factor originates from Brown[76][77]. This correction factor is a function of alloy ratio and is applied to decrease the overall factor based on alloy type.

3.4 Auxiliary Cost Factors

The factorial estimation techniques regularly stop at the total depreciable capital stage or before at battery limit investments. Additional cost items should be added to come to a full estimate.

3.4.1 Additional Cost Items

Consulting Seider et al.[17] leads to the cost structure of table 3.17. Tabulating values for the additional cost items from 1975 literature onwards in table S.1 found in appendix S, provides an overview of conventional applied values. Most factorial techniques themselves provide rough or no estimates at all, therefore the values may be replaced by the ones reported in the list.

Table 3.17: The cost structure of additional costs on top of TDC as given by Seider et al.[17]

Total depreciable capital	**TDC**
+ Land	
+ Royalties	
+ Plant start-up	
Total permanent investment	**TPI**
+ Working capital	
Total capital investment	**TCI**

Land

Land is non depreciable item for it hardly decreases in value over time. The acquirement of land may not be a necessity for extensions or replacements projects. The acquisition price of land may vary greatly between nations but also on a regional scale. Table S.1 lists typical numbers for estimating land costs within the estimate. The numbers do roughly agree, however an estimate made on local land price and area necessary to locate the plant is more accurate.

Royalties

Table S.1 shows that only one source (Seider et al.[17]) accounts for royalties and only if necessary. Other publications do estimate costs for royalties, however considered as an OpEx rather than CapEx. A rule of thumb is in the range of 1-5% of sales.

Start-up Expenses

The costs associated with start-up are dependent on the type of process, past experiences, connections to other plants or locations and operator training as described by Feldman[100]. Humpfreys[10] indicates two types of start-up expenses: Expected expenses associated with operations such as personnel training, extra working shifts and producing off-spec products. The second type are technical expenses such as extra adjustments to the equipment pieces are process.

Working Capital

Extra cash is detained to provide for working capital (WC). Some may think of working capital as liquid assets that may easily be recovered, however this is mostly only true at with high losses. In some cases the necessary working capital is higher than the F.O.B. equipment cost, this shows the urgency of making a reasonable estimate. Although ballpark figures are given in table S.1, it is worthwhile to base the working capital estimate on a more thorough analysis. Lyda[101] has published a method to decently do so. The estimate is based on time averages of raw materials, products and other items in inventory and accounts receivable minus accounts payable and part of the sales taxes. Every part has its own typical payment time scale.

3.4.2 Location Factors

Cost for various items vary among locations. Materials and equipment pieces are not subject to this variation for they are often shipped from across the globe. However the employment of local workforce, local regulations, taxes, freight and currency related matters are subject to change per geographical location. More background and the way to implement location factors is described in appendix T.

3.5 Cost Estimation Software Tools

Software tools for factorial cost estimation exist. The goals of applying software tools rather than the original factorial method are twofold: The elimination of mistakes easily made in execution by hand and time saving. However there is a cost: The loose of sight on the internal procedures.

The types of cost estimation software tools are briefly introduced, a general analysis is included at the end of this chapter.

3.5.1 Tool types

Three types of software tools implementing factorial techniques for chemical plants are identified, see table 3.18. These are elaborated in the following section.

Table 3.18: Three types of cost estimation software tools with the corresponding works.

Types	**Tools**
Online databases	mhhe, Richardson
Excel sheets	SCENT, CapCost, DFP, CCEP, EconExpert
Design programs	AspenPEA

Online Databases

This type of software tool is a digitalisations of cost databases and do not represent a full factorial technique. The data for equipment cost from Peters, Timmerhaus and West[89] is published by the authors in an online environment: mhhe[106]. It is freely accessible and converts size parameter input to a purchase price equipment list converted to date using CEPCI.

Richardson is an enterprise collecting, processing and selling industrial cost data. Their database is much more detailed than necessary for appliance in factorial techniques. It contains both CapEx and OpEx data, and for example construction schedules. Their databases are employed by 3rd parties such as Cleopatra, a cost estimating consultancy company or AspenPEA.

Excel Sheets

Most software tools are written either in Excel or Visual Basic which are similar. Conversion of existing factorial methods into excel sheets results in the tools. Developers and the actual factorial method it is based upon are listed in table 3.19. These methods are easily acquired, either by purchase of their publications or contacting the developers.

Table 3.19: The basis of Excel type cost estimation software tools, authors and factorial methods.

Tool	Based on method by...	Developed by...
CapCost	Turton et al.[45]	Turton et al.[45]
CCEP	Seider et al.[17]	Wong[107]
DFP	Sinnott and Towler[46]	Huang[108]
EconExpert	Ulrich[80]	Vasudevan and Agrawal[109]
SCENT	Woods[44]	Ereev and Patel[110]

Every tool follows the exact same approach as the factorial method it is based upon. Only CapCost and SCENT provide possibilities to extend the battery limit estimate by including outside battery limit investments, the latter not based upon the same factorial method. Additionally CapCost and SCENT also provide methods to do analyses including OpEx parameters.

Focussing on battery limit investments the input/output structure of the five methods is very similar, see figure 3.5 in which key parameters may be volume, size, power, etc. Only SCENT deviates slightly from this approach, for Woods'[44] method estimates instrument costs seperately, therefore these are required as an extra input.

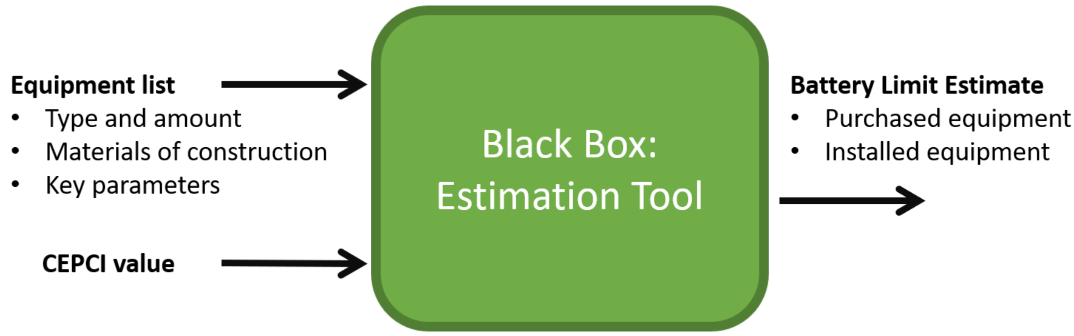

Figure 3.5: The input/output structure of excel type estimation software tools for determining battery limit investments.

Design Programs

A widely employed program is developed by AspenTech, which is a design and simulation program for chemical plants. The design parameters are transferred directly to a coupled program: Aspen Process Economic Analyser (AspenPEA). This program converts the parameters into a CapEx estimate (and more), the technique employed for the estimate is not shared by AspenTech however claimed to be based on installation models based on industrial design parameters. Their data was extracted and cast into ordinary cost curves by Loh[72] and Symister[38]. When already making a design in Aspen technology, the switch to cost estimation is rather convenient. However a greater amount of effort is required when the design work is performed on another platform.

An especially convenient feature of AspenPEA is the possibility to calibrate it to company data, specialising the estimate to enterprise requirements. Obviously the data should be available and preferably be similar project types as the required estimate. Overall AspenPEA is a popular technique, however from an analyses point of view it does not provide much information on the internal workings of the estimation method, consequently analysis about the program are limited.

Other design programs are existent, however these apply to oil and gas upstream projects. Examples are Questor and Netco$ter.

3.5.2 Software Tool Performance

The main targets of cost estimating are speed, effort and accuracy. Determining the accuracy is hard. Feng and Rangaiah[111] have investigated the workings of five (mostly Excel type) software tools: CapCost, CCEP, DFP, EconExpert and AspenPEA. The tools were applied on seven case studies from textbooks including refining, petrochemical and bio-pharmaceutical processes. The study validated that the variation in equipment price between methods was larger than the variation in battery limit total estimate value. The large number of equipment pieces a construction projects comprises has a damping effect, this is theoretically shown by Cran[60].

The variation found by Feng and Rangaiah[111] in individual equipment piece prices between software tools is more than once greater than 200%. While the maximum difference of the total battery limit installed cost is slightly larger than 100%. From the latter numbers one can conclude that the methods do not match the expected accuracy of + 30% for a class 3 estimate (see chapter 2.1.1). Some factorial methods might, however without further research it is impossible to find which one is, for the actual construction cost of the investigated projects is unknown. It is known that the variations occur solely due to differences in the factorial methods, for the software tool is merely a digitalisation of these methods. Therefore it is expected that similar results are found in the case study analysis presented in this work in chapter 4, in which the reasons for differences are discussed in greater detail.

How to Improve?

Improvements boosted by scientific works are to be expected within the Excel type software tools. Both the developers and users are familiar with the format making adaptations by 3^{rd} parties easiest. The other formats are more suited for entrepreneurial activities.

Improvement of software estimation methods is not straightforward without access to industrial data, which is a general problem in the field. Therefore the author of this thesis proposes another approach (not executed in this thesis). The input/output structures are similar for all Excel type methods as shown in figure 3.5. Therefore it should be possible to merge CapCost, CCEP, DFP, EconExpert and SCENT to one software program merely requiring one input, and computing five outputs. Naturally the results of each method will differ equally in line with Feng and Rangaiah's[111] work. But this enables deeper analyses of an estimate based on multiple results as for example done on the case studies investigated in chapter 4.

The improvement is in both the fact of time savings by a factor five and the added value of comparison. Although the accuracy of each method themselves is not improved, a band of results rather than single points are presented. If the method do not converge, there are still possibilities: Investigating the basis of statistical data of each methods may give clues on which one is the most accurate for that particular case. If that is not a possibility for that case, the added value is in the estimator's knowledge that the estimation accuracy for that particular project is poor. If merely one method was applied and an accuracy of 30% was assumed, it may have led to costly decisions.

3.6 General Opportunities for Development in Factorial Methods

Building on the last chapter on how to improve cost estimation software, chapter 3 is closed by a more general question: What are possible features of future factorial techniques that might improve the estimates? Even the most contemporary methods are almost one decade old and are in need of updating. It is hard to say anything on improving the accuracy since no thorough analysis is available in literature on the matter. Some thoughts on it are discussed as follows.

Improvement is desperate for novel industrial cost data. In the second half of the 20^{th} century these were sometimes openly published for example by Kistin, Cameron and Carter[112] or Haselbarth and Berk[113]. However nowadays companies are reluctant to share this information and are only put to use internally. Three points of improvement are proposed to employ in the development of future factorial techniques without the addition of novel cost data.

- The newer factorial methods did incorporate some degree of new (and some recycled) cost data, however it is not clear to what degree. Also the type of industry, conditions, locations, etc. are not shared. This inhibits the effective accuracy of a method, especially for the Lang type. Namely if factorials or cost databases are employed that do not match the nature of that particular construction project, a deviation is expected. Hand type methods are partly shielded by the fact that each equipment type employs separate factors and are thus already partly specialised. Therefore not only identifying applicable ranges, temporal and spatial data, the type of industry should play a larger role in the setting of factorial data. For example the factors for the food industry by Marouli, Maroulis and Saravacos[65][66] (see page 26) clearly demonstrate this point. But deviations are also to be expected in for example bio-chemical and pharmaceutical industry or ore refining.

- Most factorial techniques specify the costs made within battery limits very precisely. However the outside battery limit cost estimation, which may include buildings, service facilities, yard improvements, cost of land, utilities, etc. is often performed via very rough percentage methods. Since it involves a multiplication operation, the error made in these percentage methods are directly translated to the final result. Indeed more detailed cost engineering methods for example by Guthrie[78][79] exist to calculate these costs, however this is the other extreme and is not convenient in most situations. Future methods may need to develop new factors or ways to account for the off-site costs based on design parameters. For example it may be beneficial to develop methods that allow for the implementation of known data on the project's service facilities, yard improvements, etc., while estimating the unknowns in a rough percentage manner.

- The statistical background of both cost databases and factors is poor. By publishing factorial methods or databases it is often noted that the data is extracted from certain projects or vendor quotes without being specific. It is unknown to the estimator whether a cost databases contain correlations based upon two data-points or one-hundred. From a statistical point of view it is vital to know on how much data points the correlations are based, but equally important is their internal spread. If these are being published, they would allow for a statistical analysis of the computed result and a better judgement call how to value the estimate.

Chapter 4

A Factorial Technique Comparison Study

The previous chapter was dedicated to a theoretical study on factorial techniques, both Lang and Hand types. That analysis is limiting for it does not fully comprehend the expected results from applying the various methods. The final estimate relies on the actual databases, equipment mix and other various cost items not clearly discriminated in every method. Comparison based purely on factorials is also limiting for their (in)significance, way of implementation and containment of cost items also varies among factorial methods.

It is therefore beneficial to accommodate comparison based on the actual application of methods, these are described in the following chapter. First the worked out examples of every method executed on a single case are compared. Secondly selection criteria and thereafter actual selection of methods for further analysis are given. Finally the comparison between the selected techniques is discussed with the aid of a number of case studies.

4.1 Worked out Examples

Each Lang type factorial method discussed in chapter 3.2 and Hand type in chapter 3.3 are explained by a worked out example in appendix B and C respectively. The case (also found in the appendix) is identical for every example, however the result may be quite different.

A summary of the results is included in appendix D. That section (page 113) may be consulted for comments on differences found between the individual methods. A compilation of the results is given in table 4.1. It shows the average dollar value (scaled to 2016 values), standard deviation and variance of for each class and estimate group type. Note that the standard deviation (or variance) is no measure of accuracy, but rather indicates the inner scatter of the dataset. The agreement in data for Hand-type TDC, BL-direct and Lang-type BL is high, however the amount of datapoints is also too low to draw any conclusions.

Table 4.1: Compiled averages and standard deviations from the data in tables D.1 and D.2.

		N estimates	Average [$\bar{\$}$]	Standard deviation [σ]	Coefficient of variation [$\sigma/\bar{\$}$]
TDC	**Lang-type**	6	3.20 M$	0.85 M$	0.27
	Hand-type	2	3.18 M$	0.19 M$	0.06
	Overall	8	3.20 M$	0.70 M$	0.22
BL	**Lang-type**	3	3.21 M$	0.12 M$	0.04
	Hand-type	11	3.49 M$	0.60 M$	0.17
	Overall	14	3.43 M$	0.55 M$	0.16
BL-direct	**Lang-type**	3	2.90 M$	0.99 M$	0.34
	Hand-type	2	2.07 M$	0.11 M$	0.05
	Overall	5	2.57 M$	0.86 M$	0.34

Overall it seems that the battery limit (BL) investment estimates agree the closest. This is not surprising since TDC estimates include a considering amount of assumptions on off-site facilities, which vary among methods. This leads to more diversification and thus a larger range of estimate values.

Logically the direct battery limit investment is lower in value than the BL investment for the indirect costs are not accounted for. A TDC value is expected to be higher than a BL estimate for the inclusion of outside battery limit investments. However the TDC average is slightly lower than the BL averages. Although the standard deviations and uncertainty of the data is high enough to allow this to happen by chance. Also the worked example is also merely consisting out of 7 major process units, this amount is too low to rule out the effect of the database over the effect of the applied method. Some TDC methods (Chilton[40], Aries and Newton[12], Holland et al.[63], Bejan et al.[64], and Brown[76][77]) allowed inclusion of the fact that it was an expansion project, resulting in relative low values for off-sites.

One might consider the effect of ageing, since a large variety of methods published throughout the decades are applied and converted to modern CEPCI values for comparison.

The individual battery limit type estimates are plotted against the publication year in figure 4.1. A slowly rising trend is visible, however may not be considered significant due to the uncertainty in the dataset. Also the amount of data scatter is approximately constant. The results might not be surprising for data is often recycled, for example Seider et al.[17] (2009) still refers partly back to Chilton[40] (1949) for their database.

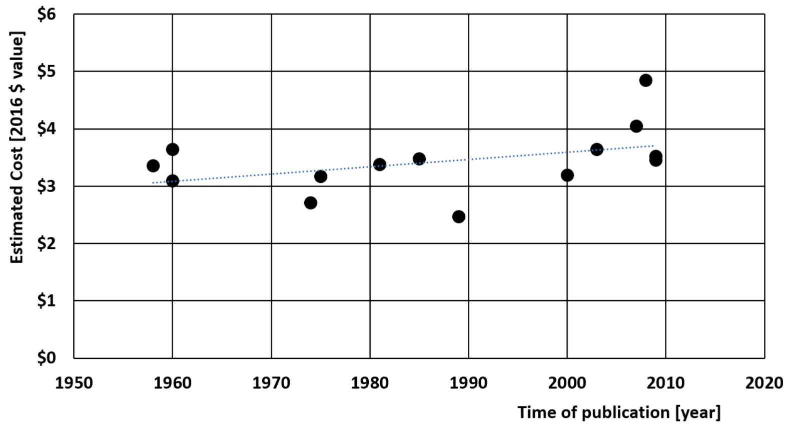

Figure 4.1: The results of the battery limit CapEx estimates plotted as a function of method publication year.

4.2 Selection of Techniques for Comparison

The selection of methods being tested on case studies is done via a set of criteria, these are as follows.

The tested method should:

- **deliver the same output**
  In order to be able to compare the results the output should be of equal merit. BL-direct methods are a poor choice, for their limited number available methods to choose from. Because in the case studies often little is known on the off-site facilities limiting the accuracy of TDC methods in these cases, battery limit (BL) investment estimates are chosen.

- **be proximate in space and time**
  For example Chauval et al.'s[61] method is based in Europe instead of the United States. Converting with the help of location factors is sketchy, consequentially it is not ideal comparison material.
  Although above it is shown that no significant effect of time is found in the example case, it is generally considered bad practise to apply older methods. It increases the risk of temporal related effects. Even though an effect on final value was not found, an difference between particular cost items is expected to be observed for their escalation is considerably different (see figure 2.3 on page 14). Ideally the newer methods (+/- 20 years) are tested for nowadays they are mostly applied. This cancels out all Lang type BL techniques.

- **easily being executed with limited information** Because the case studies are extracted from external sources, the information is mostly limited to equipment lists. Therefore essential project details are sometimes unknown.

Table 4.2: The selected combinations for the comparison study among cases.

Method	**Database**
Woods (2007)	Woods (2007)
Turton et al. (2008)	Turton et al. (2008)
Gerrard (2000), Brennan and Golonka (2002)	Seider et al. (2009)
Gerrard (2000), Brennan and Golonka (2002)	Sinnott and Towler (2009)
Hand (1958)	Seider et al. (2009)
Hand (1958)	Sinnott and Towler (2012)

This leads to the following four combinations, shown in table 4.2. Gerrard[15] and Brennan and Golonka[86] are considered to be the same technique. Because the database by Gerrard is not that extensive, older than the others and based in Europe the more novel databases by Seider et al.[17] and Sinnott and Towler[46] are adopted. This also provides the opportunity to visualise the effect of database.

Secondly a quick comparison is made to applying applying the (aged and simple) Hand factors. Which are easier and quicker to apply than the carefully adapted designed factors of Gerrard, Brennan and Golonka. It will be interesting to investigate the gain by terms of estimating effort.

Turton et al.[45] was found to be approximately the average of five methods tested by Feng and Rangaiah[111]. Woods is interesting to implement in the comparison for it has not been done before in literature.

4.3 Results from the Comparative Study

In the following section the selected case studies will be shortly introduced. The general outcomes are shown and elaborated next, afterwards the most interesting conclusions from individual cases are discussed. Not all results are shown in this section, more profound analyses and explanations on every case are given in appendix U.

4.3.1 The Case Studies

Table 4.3 shows the selected case studies, which are all limited to the battery limit investment. Cases 1 to 6 are couples of the same processes in large and small versions investigated by the National Renewable Energy Laboratory[114] in 2006. Case 7 and 8 are modules in a investigation into the feasibility of wind powered ammonia economy by Morgan[115]. Case 9 is a constructed project, now for sale by International Process Plants[116]. Both cases 10 and 11 are projects evaluated by students as part of a conceptual design project. And the last case is an evaluation by Cameron et al.[119] of an ethanol to ethylene unit supposed to run on bio-ethanol in Brazil. Almost all cases involve a significantly present gas phase, which is of influence on the results as shown later.

Table 4.3: The selected case studies.

	Process	**Capacity [ton/day]**	**Main Phase(s)**	**Literature Source**
1	Fluid Catalytic Cracking (small)	100,000	Gas	NREL[114]
2	Fluid Catalytic Cracking (large)	2,500,000	Gas	NREL[114]
3	Steam Methane Reforming (small)	0.11	Gas	NREL[114]
4	Steam Methane Reforming (large)	1,100	Gas	NREL[114]
5	Natural Gas Liquid Expander (small)	460	Gas/Liquid	NREL[114]
6	Natural Gas Liquid Expander (large)	3,400	Gas/Liquid	NREL[114]
7	Ammonia Synthesis Loop	300	Gas	Morgan[115]
8	Cryogenic Air Separation	250	Gas/Liquid	Morgan[115]
9	Methanol from Syngas	310	Liquid	IPPE[116]
10	Soybean Oil Body Extraction	12.5	Liquid/Solid	van Amsterdam et al.[117]
11	Methylamines from Methanol and Ammonia	165	Gas/Liquid	Mansouri et al.[118]
12	Bio-ethanol to Ethylene	3800	Gas/Liquid	Cameron et al.[119]

4.3.2 The Overall Results

The final results of the 12 case studies are shown in table 4.4, in which the installed costs for each method and case combination is listed. The average is accompanied by the standard deviation and coefficient of variance, the latter implies the assumption that the result may be regarded as normally distributed. The coefficient of variation γ is a measure of the internal data spread around the average. Therefore a low figure shows a high agreement among the methods applied.

Table 4.4: The installed costs for the twelve cases in millions of 2016 dollars (CEPCI = 541.7). [*] Accuracy of reference is doubtful.

Case	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Woods	11.1	60.5	1.5	140.2	14.2	48.9	40.9	11.6	26.0	10.6	11.4	36.2
Turton et al.	3.3	105.6	0.5	177.9	11.1	49.5	29.2	10.6	24.7	16.0	10.1	48.0
Seider et al. - IChemE	6.2	38.8	1.4	110.4	15.0	46.7	42.3	14.3	24.6	7.5	12.2	42.2
Seider et al. - Hand	5.5	36.9	0.8	125.8	13.1	47.2	38.6	11.7	22.8	7.3	11.3	39.2
Sinnott & Towler - IChemE	11.8	66.8	2.8	154.4	20.1	53.4	61.4	19.1	28.9	10.1	20.6	47.6
Sinnott & Towler - Hand	13.0	71.0	2.6	217.3	20.9	63.0	72.1	15.7	30.8	11.3	22.7	59.9
Average [$\bar{\$}$]	**8.5**	**63.3**	**1.6**	**154.3**	**15.7**	**51.5**	**47.4**	**13.8**	**26.3**	**10.5**	**14.7**	**45.5**
Standard Deviation [σ]	3.6	23.0	0.8	35.3	3.6	5.6	14.6	2.9	2.7	2.9	5.0	7.7
Coefficient of Variation [$\sigma/\bar{\$}$]	**0.43**	**0.36**	**0.53**	**0.23**	**0.23**	**0.11**	**0.31**	**0.21**	**0.10**	**0.28**	**0.34**	**0.17**
Reference	**11.9**	**111.3**	**0.27**	**264.6**	**13.1**	**50.3**	**101.2***	**12.2**	**27.4**	-	-	**46.0***
Error in Average	+40%	+76%	-90%	+71%	-17%	-2%	+114%	-12%	+4%	-	-	+1%

A reference value is listed in table 4.4, and compared to the found average value. The reference values for cases 1 to 6 are extracted from the report by NREL[114] and is based upon vendor quotes, which are considered to be more reliable than factorial methods. The reference for case 7 is based upon two data points (published by Duncan[120] and Tremel et al.[121]), both significantly larger in capacity than case 7 and was extrapolated and is therefore not a reliable estimate. Case 8's reference is composed of Air Liquid's[122] standard packages for cryogenic air separation plants and Kreutz et al.'s[123] techno-economic analyses with commercially ready technology. The reference value of case 9 is relatively solid, it is based upon cost data of nine newly constructed plants in the U.S. described by Turaga[124]. No reference data was found for the cases 10 and 11. Case 12's reference is poor, for the two data points found are similar in cost but differ significantly in capacity. Data was extracted from Mohsenzadeh[125] and the case developers: Cameron et al.[119]

However individual case remarks are placed in the next chapter (4.3.3) and in depth analyses are shown in appendix U, a few overall trends are visible and summed in the following pages.

Successful estimates

The accuracy of a factorial method is considered to be such that the actual capital investment is within -25% to +30%, see chapter 2.1.1. Therefore in this a estimate is considered successful if it fulfils this requirement. Table 4.5 shows the amount of successful estimates (out of 10 possible) and the absolute average error per method and the averaged methods.

Table 4.5: The amount of successful estimates according to factorial estimation guidelines.

	Successful estimate count	**Absolute average error**
Computed Average from Methods	**5x** (5, 6, 8, 9, 12)	43%
Woods	**6x** (1, 5, 6, 8, 9, 12)	46%
Turton et al.	**6x** (2, 5, 6, 8, 9, 12)	66%
Seider et al. - IChemE	**5x** (5, 6, 8, 9, 12)	69%
Seider et al. - Hand	**5x** (5, 6, 8, 9, 12)	71%
Sinnott & Towler - IChemE	**4x** (1, 6, 9, 12)	38%
Sinnott & Towler - Hand	**6x** (1, 4, 6, 8, 9, 12)	33%
Average of above	-	54%

No decisive conclusion on the most successful method may be made based upon the presented data, the differences are too small. The score of both Sinnott & Towler's databases are an example of this, the amount of successful estimates differs by two, however this is only due to a slight crossing of the requirement boundary and does not represent a consistent difference. The success rate seems more dependent on the type of case study than on the method, for the successful attempts were mostly made among the same cases: 1, 5, 6, 8, 9 and 12.

The computed average has no more successful estimates than individual methods, however the absolute average error is lower than the average error of the separate methods. If the methods are combined at least the certainty of the estimate increases, individual method deviations (such as in Seider et al. and Turton et al. in case 1) drive the average away from the correct value.

Influence of Factors versus Databases

Based on the result shown in table 4.5 it is clear that the IChemE method, which requires a higher effort to perform, did not score better than the Hand method, which is relatively straightforward. It is somewhat surprising for the Hand method is relatively old and is static in appliance. While the IChemE method is dynamic, has multiple inputs and is supposed to be more adaptive to different type of projects. The main advantage should be the lowering of factors for expensive equipment items. Consequently sometimes the overall factor in the IChemE factor was higher than Hand's and sometimes lower, however this was not necessarily beneficial for the end result.

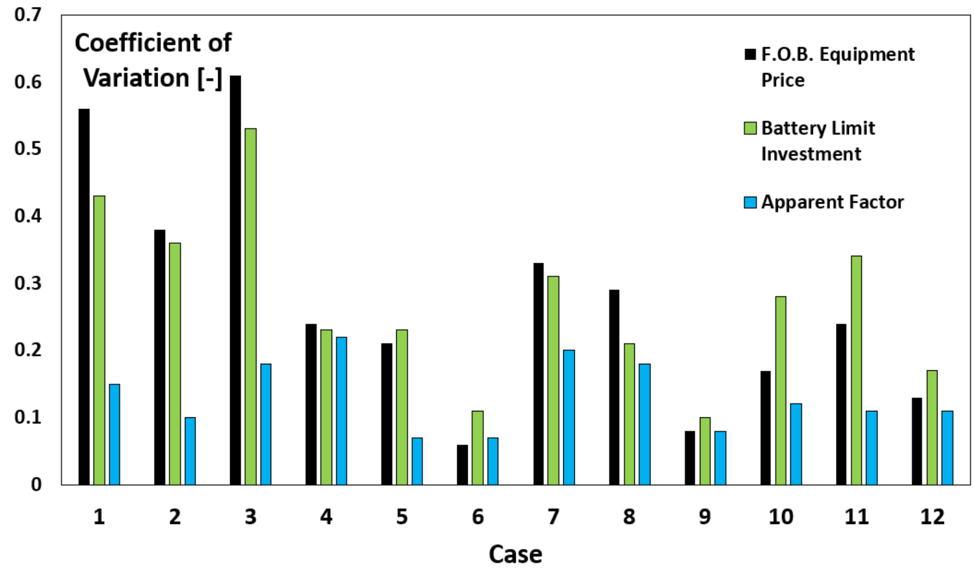

Figure 4.2: The coefficient of variation for F.O.B. equipment price, installed battery limit cost and observed apparent factor.

$$ApparentFactor = \frac{Installed\ \ BL\ \ [\$]}{\sum\ F.O.B.\ \ equipment\ \ [\$]} \tag{4.1}$$

Naturally the influence of the database is investigated, conclusions are drawn on the basis of table 4.2. The apparent factor is defined as shown in equation 4.1. The coefficient of variation for this factor is in every case (except 6) the lowest value compared to the coefficient of variation for installed battery limit cost and the total F.O.B. equipment cost. This leads to the conclusion that the variation in battery limit cost is mostly due to the variation in F.O.B. equipment cost.

And thus is influence of the database higher than the influence of the factor, also partly explaining the results observed in table 4.5. It shows that the absolute average error of the same databases is similar, independent on the applied method. The same is true for the final battery limit investment data in table 4.4, in which the battery limit estimate values are more similar for equal databases than equal methods. From that analysis it is clear that the database of Sinnott and Towler produces higher estimates than Seider et al., where Woods and Turton et al. are in between. Especially Woods' estimate is often close to the average. Consequentially it is made clear that it may be beneficial for future research to move the focus to databases rather than factorial techniques.

Another topic is the versatility of the databases. The database of Woods is extensive in types of equipment, applicable ranges, pressure and materials factors specific to the equipment piece and the possibility to choose between size parameters. Sinnott & Towler's is most limited in that sense.

Project size

Project size, defined as the number of process units within the estimate, is of influence on the expected accuracy. Every output of a database is assumed to deviate around the average value. If the number of units, which may be considered as statistical samples, within the process flow sheet increases, statistical theory predicts a decrease in variance. If indeed the average value is actually the correct real value, then the error in the estimate decreases as a consequence.

As expected the dataset shows (see figure 4.2) a decrease in the coefficient of variation if the number of units increase. Secondly figure 4.4 shows the correlation between the coefficient of variation and the absolute average error. No surprises are found in this case either. The error naturally rises if the coefficient rises for the error is a summation of deviations. From these two knowns it is now concluded that the theorem stated above applies: Higher estimate accuracy is expected for projects containing a high amount of process units. A similar statement by the way was already made by Cran[60], however was only based on theory and not on experimental results.

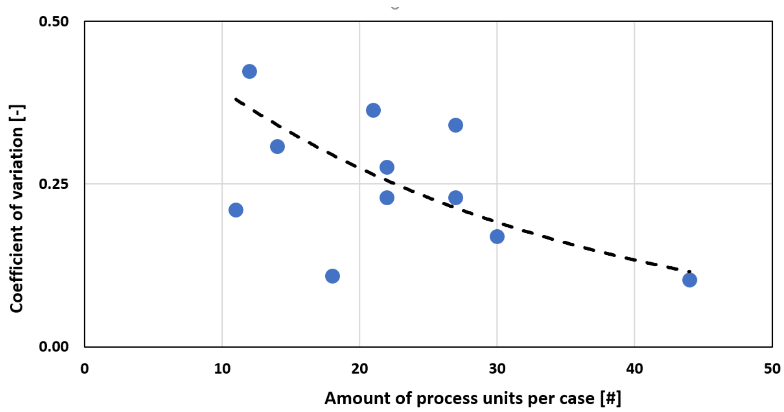

Figure 4.3: The coefficient of variation as a function the number of units for all cases.

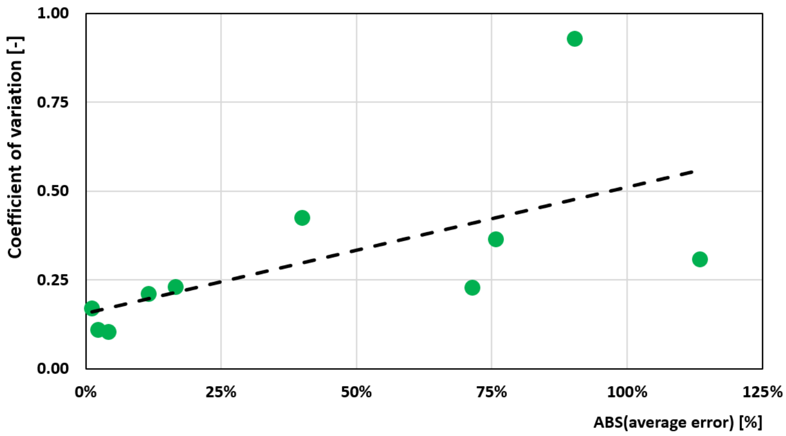

Figure 4.4: The absolute value of the average error versus the coefficient of variation for all cases.

A similar trend is visible when the project size was defined as the total battery limit investment money sum. However the trend was less evident. This was due to the fact that higher valued projects not necessarily contain more equipment pieces, but may instead consist of larger pieces leading to a assimilated effect.

4.3.3 Auxiliary Conclusions

All individual case results are tabulated in appendix U, the most notable conclusions are additionally included in this section.

Variations among Equipment Types

A test on accuracy of equipment category is not available due to the unavailability of reference data on each category. However the agreement between methods may be compared: The average scatter of data per common equipment type is depicted in figure 4.5. Note that the amount of experiments involved with each category may differ, therefore the conclusions should be viewed with caution.

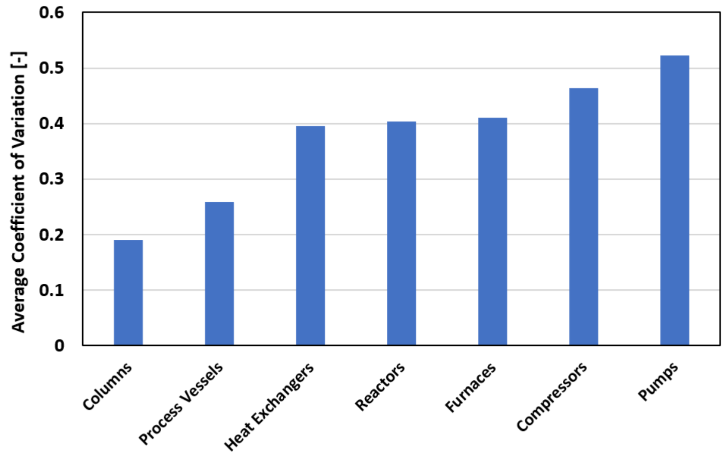

Figure 4.5: The average amount data scatter (coefficient of variation) per equipment type.

Generally the agreement, which is measured by the coefficient of variation, on process vessels and columns is high. The scatter of data points for other common equipment types are found to be approximately equal. Note that a low coefficient of variation, and thus a high agreement among methods, is expected to be an indication of higher accuracy. However this is solely true if indeed the methods revolve around the actual average as discussed on the previous page.

A significant part of the variation in compressor data is due to the data acquired via Sinnott & Towler. Their database contains prices deviating from the other databases by a factor 2 to 4 on the high side. This was also observed by the case study research of Feng and Rangaiah[111].

Analyses on Individual Cases

The outcome of all tested factorial estimation techniques correspond relatively well with the reference value of cases 5, 6, 8, 9 and 12. Strikingly these correspond to all liquid phase processing case studies that have a reference value attached. Whether this is merely a coincidence or an acutal consequence of database building on the petro-chemical industry (largely involving fluids) could not be statistically verified and asks for closer examination in future case studies.

For some other case studies the estimates did not match the reference value closely. An attempt is made to account these differences. The estimates of the FCC cases, both small and large (case 1 and 2), were off by most methods. This is probably due to a large portion of the cost being a reactor with complex internals. The reference value from a manufacturer's quotation is able to implement the complexity whereas the factorial techniques are too superficial. Another indication is that all estimates are lower than the reference values. In case 1 Woods came close to the reference value, for his database contains a riser, which the other databases don't. Also Sinnott and Towler's estimate was close, however this was due to the overestimation of compressor costs compensating for other underestimates and not a right reflection of cost distribution, which was accurate Woods' case. For case 7, the design did probably not contain all units present in the reference value, so the reference value is off rather than the estimate. Although it should noted that the internal data scatter of the tests is high.

The estimation for both SMR cases (case 3 and 4) both failed to coincide with the reference value. The reason is the fact that case 3 has a very small capacity, the correlations for equipment F.O.B. prices were often out of range. The same is true for case 4 at the high end.

A interesting statistical phenomena occurs and is not merely secluded to case 3. This is shown by comparing figure 4.6 and 4.7, a relative good and poor match between estimates and reference data respectively. A normalised probability density assuming a normal distribution (which in reality is skewed) is constructed from the six data points. If the scatter is low (low value of the coefficient of variation γ) the curve is narrow. Case 6 shows a narrow confidence interval and good correlation with the reference value in green. In case 3 the error between the estimates and the reference data is large. However the reference value still falls within the 95% confidence interval exactly because the scatter of data points is large. Therefore the test by default is not very predictful if the scatter is large. This occurs in many other estimates shown in appendix U. A more thorough test based on a higher number of estimates is necessary to narrow the curve.

Figure 4.6: The constructed normal distribution curve for case 6 (NGL large). The green line indicates the reference value.

Figure 4.7: The constructed normal distribution curve for case 3 (SMR small). The green line indicates the reference value.

Chapter 5

Conclusions & Recommendations

The historical fabric of factorial method development was investigated, organised and shown in the literature tree. Methods were discriminated between Lang and Hand type techniques. The Lang type main characteristic is that a single factor or merged multiple factors work on the sum of equipment cost, while Hand types associate a factor with each single equipment piece.

The methods were subdivided into four Lang type categories of which two exemplary: The 'art rather than a science' movement, directed by Chilton pressing the importance of the estimator's skill above other considerations. Peters and Timmerhaus lead the 'improved Lang factor' category, breaking down the Lang factor into separate factors accounting for individual cost items or occasions.

Six Hand type subcategories were identified. An influential branch initiated by Cran estimates instruments seperately. A well-known category is based on Guthrie's detailed method introducing a modular concept of plants, following authors have simplified the approach. The methods endorsed by IChemE introduces factors depending on equipment value rather than type.

Throughout factorial cost estimation literature general trends are visible. Improvements have been achieved by diversifying factors to specialised equipment types and circumstances. Although factorial data has been updated regularly (not in the past decade), the statistical backing remains questionable. The scientific field is limited by the amount cost data made available by the industry; Even leading publications do not critically examine the accuracy of their work. Improvement in future methods is gained if statistical parameters, such as standard deviation and amount of data points, would be published next to averages. A second issue is the assessment of indirect costs and cost made outside of battery limits; definition are poorly defined and estimation methods approximate. Improvement of methods' accuracy may be gained by better cost item definition and cost estimation based on physical parameters rather than percentage methods.

Software tools have the advantage of being fast and exact in reproducing a method. They may partly help overcome the uncertainty on factorial estimation accuracy by simultaneous estimate execution and analyses of multiple methods.

In the second part of this work all described methods were tested on a single exemplary case study. Methods merely estimating costs within battery limits showed the largest agreement. No significant difference between older and newer methods was observed.

Subsequently six selected database-method combinations were tested on twelve case studies found in literature, containing mainly gas and liquid processing plants with varying in capacity. The success rate of estimates (4/10 to 6/10) were proven to be more dependent on case type, namely liquid processing, than type of method. A process employing a larger amount of process units is estimated more accurately due to averaging out of systematic errors. Secondly it was shown that databases had a larger influence on the final result than factors did. A shift of focus in research to databases rather than methods is justified. Variation of costs was larger between equipment types (average 48%, except columns 16%) than the final result (27%).

Lastly statistical analysis of multiple methods proved to be a valuable tool in assessing the (un)certainty of that particular case study. With the help of cost estimation software it has potential to be the basis of future improvements in the field.

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List of Abbreviations

ACCE	Aspen Capital Cost Estimator
Al	Aluminium
BL	Battery Limits
BM	Bare Module
CapEx	Capital Expenditure
CEPCI	Chemical Engineering Plant Cost Index
Co	Copper
CS	Carbon Steel
DIC	Direct and Indirect Plant Cost
DPC	Direct Plant Cost
DACE	Dutch Association of Cost Engineers
EC	Equipment Cost
ENR	Engineering News-Record
F.O.B.	Free on Board
Gl	Glass
Gr	Graphite
Ha	Hastelloy
IChemE	Institution of Chemical Engineers
Mo	Monel
MS	Marshall-Swift (Process Industry Index)
NF	Nelson-Farrar (Indexes)
Ni	Nickel
OpEx	Operational Expenditure
P&F	Plate and Frame
PM	Physical Module
S	Services
SS	Stainless Steel
S&H	Storage & Handling
S&T	Shell and Tube
TDC	Total Depreciable Costs
TCI	Total Capital Investment
TPI	Total Permanent Investment
TM	Total Module
Ti	Titanium
U	Utilities

List of Symbols

Quantaties and units

C	Capital Cost	$
E	Equipment Cost	$
$\bar{E}$	Mean Equipment Cost	$
F	Factor	-
F_{H}	Hand Factor	-
F_{L}	Lang Factor	-
f	Correction factor	-
ffv	Total field-fabricated vessel cost	$
hex	Total heat exchanger cost	$
K	Constant	-
L	Labour component	-
M	Material component	-
N	Number of functional units	#
n	Exponent in the sixth-tenth rule	-
n	Number of equipment pieces	#
pd	Total pump including driver cost	$
S	Size parameter	-
ts	Total tower shell cost	$
W	Wage	$ hour^{-1}
γ	Coefficient of variation	-
η	Productivity	-
ϕ	Combined Factor	-

Subscripts

A/A	Additions / Alterations
AM	Auxiliary materials
B	Buildings
BL	Battery limits
BM	Bare module
CE	Construction expenses
C	Contingencies
CF	Contractor's fee
CP	Chemical process
CV	Civil
DIC	Direct and indirect plant costs
DPC	Direct plant costs
E	Electrical installations
$E\&C$	Engineering and construction
$E\&S$	Engineering and supervision
F	Auxiliary Facilities
FO	Foundations
FP	Fireproofing
I	Instruments
IL	Installation labour
I/L	Insulation / Lining
L	Land
$L\&M$	Labour and material
M	Miscellaneous
$M\&E$	Mechanical and electrical
MO	Management overhead
MOC	Materials of construction
MUE	Miscellaneous unlisted equipment
O	Off-site
PM	Physical module
P	Piping
PA	Paint
PU	Process units
SU	(Steel) Support Structures
S	Services
SLC	Secondary labour components
SMC	Secondary materials components
$S\&H$	Storage and handling
SF	Size Factor
T	Total
TCI	Total capital investment
TDC	Total depreciable costs
TFI	Taxes, freight and insurance
TM	Total module
t	At time t
U	Utilities
W	Working capital
Y	Yard improvements
$Y\&L$	Yard improvements and land

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Appendix A

Cost Checklist

The full list checklist of cost items published by Peters and Timmerhaus[14] is itemised below. This list is just an example for the reader of this thesis to give an idea of the extend of estimations, many more authors have published versions which show differences in cost categorisation. An abbreviated version is already shown in chapter 2.2.

Direct Costs

- **Purchased equipment**
  All equipment listed on a complete flow sheet
  Spare parts and non-installed equipment spares
  Surplus equipment, supplies and equipment allowance
  Inflation cost allowance
  Freight charges
  Taxes, insurance and duties
  Allowance for modifications during start-up

- **Purchased equipment installation**
  Installation of all equipment listed on a complete flow sheet
  Structural supports, installation and paint

- **Instrumentation and controls**
  Purchase, installation, calibration and computer tie-in

- **Piping**
  Process piping: Carbon steel, alloy, cast iron, lead, lined, aluminium, copper, ceramic, plastic, rubber and reinforced concrete
  Pipe hangers, fittings and valves
  Insulation: Piping and equipment

- **Electrical equipment and materials**
  Electrical equipment: Switches, motors, conduit, wire, fittings, feeders, grounding, instrument and control wiring, lighting and panels
  Electrical materials and labour

- **Buildings (including services)**
  Process buildings: Substructures, superstructures, platforms, supports, stairways, ladders, acces ways, cranes, monorails, hoists and elevators
  Auxiliary buildings: Administration and office, medical or dispensary, cafeteria, garage, product warehouse, parts warehouse, gaurd and safety, fire station, change house, personnel building, shipping office and platform, research laboratory and control laboratory
  Maintenance shops: Electric, piping, sheet metal, machine, welding, carpentry and instrument
  Building services: Plumbing, heating, ventilation, dust collection, air conditioning, building lighting, elevators, escalators, telephones, intercommunication systems, painting, sprinkler systems and fire alarm

- **Yard improvements**
  Site development: Site clearing, grading, roads, walkways, railroads, fences, parking areas, wharves and piers, recreational facilities and landscaping

- **Service facilities**
  Utilities: Steam, water, power, refrigeration, compressed air, fuel and waste disposal
  Facilities: Boiler plant incinerator, wells, river intake, water treatment, cooling towers, water storage, electric substation, refrigeration plant, air plant, fuel storage, waste disposal plant, environment controls and fire protection
  Non-process equipment: Office furniture and equipment, cafeteria equipment, safety and medical equipment, shop equipment, automotive euqipment, yard material-handling equipment, laboratory equipment, locker-room equipment, garage equipment, shelves, bins, pallets, hand trucks, housekeeping equipment, fire extinguishers, hoses, fire engines and loading stations
  Distribution and packaging: Raw material and product storage and handling equipment, product packaging equipment, blending facilities and loading stations

- **Land**
  Surveys and fees
  Property cost

Indirect Costs

- **Engineering and supervision**
  Engineering costs: Administrative, process, design and general engineering, drafting, cost engineering, procuring, expediting, reproduction, communications, scale models, consultant fees and travel
  Engineering supervision and inspection

- **Construction expenses**
  Construction, operation and maintenance of temporary facilities, offices, roads, parking lots, railroads, electrical, piping, communications and fencing
  Construction tools and equipment
  Construction supervision, accounting, timekeeping, purchasing and expediting
  Warehouse personnel, warehouse expense and gaurds
  Safety, medical and fringe benefits
  Permits, field tests and special licenses
  Taxes, insurance and interest

- **Contractor's fee**

- **Contingency**

Appendix B

Examples: Factorial Techniques - Lang Type

In this appendix worked out examples of each method discussed in chapter 3.2 are presented. All are applied to the same hypothetical case study extracted and slightly adapted from the book by Seider et al[17]. This section's purpose is mainly to clarify the ways of applying each capital cost estimation technique. However the results are also compared briefly in chapter 4.1. Depending on the accessible information each method is worked out as much as possible. Only CEPCI is adopted as the measure of indexing because it is most general and extends back to the 1940's. Separate indexing per equipment type would also be a possibility however is considered to be too tedious and unnecessary for the applied ranges are small.

In a hypothetical fluid processing plant the following main plant items are to be installed within battery limits:

- Two carbon steel centrifugal pumps (one standby) that may each handle 1.50 m^3 min^{-1} and produce a 15 bar head at ambient temperature.
- A process heater with tubes made out of carbon steel. The pressure is 15 bar and heat duty is 6 MW.
- A distillation column with 1.5 meter diameter, 25 sieve plates, and 0.6 meter tray spacing. The pressure is 15 bar and the material of construction is 316 stainless steel.
- A carbon steel agitated vessel (vertical) being able to contain 50 m^3 at ambient pressure and temperature, height is 10 meter. The agitator's power consumption is 60 kW.
- A shell-and-tube heat exchanger with 300 m^2 transfer surface, floating head, a carbon steel shell and 316 stainless steel tubes operating at 10 bar.
- A shell-and-tube heat exchanger with 750 m^2 transfer surface, floating head, and carbon shell and tubes operating at 15 bar.

Other known facts for the chemical plant are that:

- The construction project is being build as an extension to an already operating factory.
- No additional utilities, except for an extra cooling tower (10 m^3 min^{-1}), are required to be installed.
- The constructed equipment is placed outside and does not require acquirement of new land.
- Because of the use of dangerous chemicals the amount of instrumentation is relatively high.
- The process is well known, however has not been implemented before by the company and needs relatively high amount of engineering.
- The site is interconnected with other enclosed operations and requires additional integrations lines for the new product.

B.1 H.J. Lang

Because Lang[57][58][59] only provided the Lang factor and no cost database for equipment pieces, the equipment cost data of Chilton[40] is employed (see next section B.2 for two reasons. The two publications were published in close proximity and both methods have installed equipment data as an input rather than a F.O.B. price. The found installed equipment cost with Chilton's database is $114,300 in 1951 dollar value (CEPCI 80.4). Then apply the Lang factor for fluid processing (4.74) as done in the equations B.1 and B.2.

$$C_{\text{TDC}} \ = \ F_{\text{L}} \ \cdot \ \sum_{k=1}^{n} E_{\text{k}} \tag{B.1}$$

$$C_{\text{TDC}} \ = \ 4.74 \ \cdot \ \$114,300 \ = \ \mathbf{\$541{,}800} \tag{B.2}$$

B.2 C.H. Chilton

The equipment piece installed prices are extracted from cost curves out of Chilton's paper[40]. The installed cost includes the basic equipment item plus installation labour, foundation or supports, installation of drive equipment and related auxiliaries, insulation, painting, and any piping considered an integral part of the equipment.

Table B.1: Installed equipment cost extracted from Chilton[40]. Shown as 1951 (CEPCI = 80.4) prices.

Unit	Installed cost	Additional notes
2 Centrifugal pumps	$5,800	Correlated to shaft power, assumed water density and 70% pump efficiency
Process heater	$61,000	
Distillation column	$30,000	$1,200 per tray, no SS-316 sieve trays in database, SS bubble plate most closely related
Agitated tank	$8,100	Merely based on vessel volume and not on agitator
CS/SS heat exchanger	$5,500	
CS heat exchanger	$3,900	
Total:	**$114,300**	

The factor are applied according to equations B.3 and B.4. In tabular form the result may be computed according to table B.3, the argumentation for the factor value is given in table B.2. The computation reveals that the total depreciable cost is estimated at $380,400 dollar based in 1951.

$$C_{\text{physical}} \ = (1 + F_{\text{P1}} + F_{\text{P2}} + F_{\text{B}} + F_{\text{F}} + F_{\text{I}}) \ \cdot \ \sum_{k=1}^{n} E_{\text{k}} \tag{B.3}$$

$$C_{\text{TDC}} \ = (1 + F_{\text{E\&C}} + F_{\text{C}} + F_{\text{SF}}) \ \cdot \ C_{\text{physical}} \tag{B.4}$$

Table B.2: The values and arguments for choosing the values of factors applied in Chilton's method. See chapter 3.2.1 on page 19 for the appropriate ranges.

Factor	Value	Argumentation
Process piping *P1*	0.45	Average for fluid processes
Outside lines *P2*	0.05	Closely integrated complex
Manufacturing buildings *B*	0.125	Average for outdoor construction
Auxiliary facilities *F*	0.10	Merely one extra cooling tower
Instrumentation *I*	0.15	Highly instrumented process
Engineering and construction *E&C*	0.43	New process and highly integrated
Contingencies *C*	0.25	Subject to change and highly integrated
Size factor *SF*	0.10	High throughput, however limited in amount of units

Table B.3: Computation in 1951 dollar value of the total depreciable capital according to Chilton's method in tabular form.

Cost item	Price
Installed equipment	**$114,300**
Process piping	$51,400
Outside lines	$5,700
Manufacturing building	$14,300
Auxiliary facilities	$11,400
Instrumentation	$17,100
Total physical cost	**$214,200**
Engineering and construction	$91,000
Contingencies	$53,600
Size factor	$21,400
Total depreciable cost	**$380,200**

B.3 R.S. Aries & R.D. Newton

Aries and Newton[12] have published their own cost database based on 1954 (CEPCI = 86.1), this is applied in table B.4. Note that a process heater is missing in the database, the price is taken from Chilton[40] and is for an already installed piece.

Table B.4: The costs for purchased equipment from Aries and Newton[12]. All prices are shown as 1954 (CEPCI = 86.1) prices. * The furnace price is from Chilton[40] and on an installed basis.

Unit	Purchased cost	Additional notes
2 Centrifugal pumps	$1,500	Including drives
Process heater	$65,300*	From Chilton[40], installed price
Distillation column	$40,300	$1,550 per tray, no SS-316 sieve trays in database, SS bubble plate most closely related
Agitated tank	$10,500	Merely based on vessel volume and not on agitator
CS/SS heat exchanger	$21,000	
CS heat exchanger	$15,000	Slightly out of range, extrapolated
Purchased:	**$88,300**	
Installed:	**$65,300**	
Total:	**$153,600**	

Aries and Newton's set of equations are presented in equations B.5 to ref B.7. The value of factors and the argumentation are shown in table B.5. The worked out equations are shown in tabular form in table B.6.

Note that the installation labour and insulation factor do not work only on the purchased price, for these items are already present in Chilton's price data. One major question mark however is whether freight and import taxes are included. Aries and Newton tabulate purchased prices, but never mention those cost items. It is chosen to leave them out of this estimate for no clear method is provided by the authors.

$$C_{\text{physical}} = (1 + F_{\text{IL}} + F_{\text{P}} + F_{\text{I/L}} + F_{\text{I}} + F_{\text{E}} + F_{\text{B}} + F_{\text{Y\&L}} + F_{\text{U}}) \cdot \sum_{k=1}^{n} E_{\text{k}} \quad \text{(B.5)}$$

$$C_{\text{DPC}} = (1 + F_{\text{E\&C}}) \cdot C_{\text{physical}} \quad \text{(B.6)}$$

$$C_{\text{TDC+land}} = (1 + F_{\text{CF}} + F_{\text{C}}) \cdot C_{\text{DPC}} \quad \text{(B.7)}$$

Table B.5: The values and arguments for choosing the values of factors applied in Aries and Newton's method. For the available ranges the reader is directed to the original book[12].

Factor	Value	Argumentation
Installation labour *IL*	0.43	Given
Piping *P*	0.86	For fluid processes
Insulation *I/L*	0.08	Given
Instruments *I*	0.30	Extensive control
Electrical *E*	0.125	Average value
Buildings *B*	0.50	Indoor construction and equipment values below $250,000
Yard improvements and land *Y&L*	0.125	Average value
Utilities *U*	0.25	Minimum additional services
Engineering and construction *E&C*	0.30	Physical cost less than $1,000,000
Contractor's fee *CF*	0.07	Average value
Contingencies *C*	0.20	Average/high value

Table B.6: Computation in 1954 dollar value of the total depreciable capital according to Aries and Newton's method in tabular form. [*] Factors only worked on purchased price.

Cost item	Price
Purchased equipment	**$88,300**
Installed equipment	**$65,300**
Installation labour*	$38,000
Piping	$132,100
Insulation*	$7,100
Instruments	$46,100
Electrical	$19,200
Buildings	$76,800
Yard improvements and land	$19,200
Utilities	$38,400
Total physical cost	**$330,800**
Engineering and construction	$99,200
Direct plant cost	**$430,000**
Contractor fee's	$30,100
Contingencies	$86,000
Total depreciable cost	**$546,100**

B.4 F.A. Holland, F.A. Watson & J.K. Wilkinson

No database is delivered by Holland, Watson and Wilkinson[63], therefore a database published in the similar time period is used. Guthrie[79] was chosen, see part C.7 how the equipment cost was calculated. The result is a field fabricated vessel of $107,100 and the other equipment pieces sum up to $126,500 in 1970 dollar value (CEPCI = 125.7). The method needs delivered to site prices as an input, therefore the average number (12%) from Guthrie[78] was employed. Then in accordance with the Holland et al. method, installed prices are calculated by employing the factor for fluid processes ϕ_1 as explained on page 22. Equations B.8 to B.10 are applied and worked out in table B.7 The factors applied are exactly like Chilton's and values are recycled from table B.2.

$$C_{\text{TDC}} = \phi_1 \cdot \phi_2 \cdot \phi_3 \cdot \sum_{k=1}^{n} E_{\text{k}} \tag{B.8}$$

$$\phi_2 = 1 + F_{\text{P1}} + F_{\text{P2}} + F_{\text{B}} + F_{\text{F}} + F_{\text{I}} \tag{B.9}$$

$$\phi_3 = 1 + F_{\text{E\&C}} + F_{\text{C}} + F_{\text{SF}} \tag{B.10}$$

Table B.7: Applying the method by Holland, Watson and Wilkinson[63], on delivered to site prices from Guthrie[78][79]. Prices are displayed on a CEPCI 125.7 basis.

Cost item	**Price**
F.O.B. equipment	$107,100
Freight, taxes, insurance	$15,200
Delivered to site	**$141,700**
Installing (ϕ_1=47%)	$66,600
Field fabricated furnace	$107,100
Installed equipment	**$315,400**
Process piping	$141,900
Outside lines	$15,800
Manufacturing building	$39,400
Auxiliary facilities	$31,500
Instrumentation	$47,300
Total physical cost	**$591,300**
Engineering and construction	$251,300
Contingencies	$147,800
Size factor	$59,100
Total depreciable cost	**$1,049,500**

B.5 M.S. Peters & K.D. Timmerhaus

Purchased prices of the equipment pieces are found in the publication of Peters and Timmerhaus[14], these are on a 1990 dollar (CEPCI = 357.6) basis. The results are shown in table B.8. Freight, import taxes and insurance are added via Guthrie's[78] approximation since no numbers are provided by Peters and Timmerhaus themselves and delivered equipment prices are needed as an input in the factorial technique.

Table B.8: The purchased prices extracted from the work of Peters and Timmerhaus[14], on a (1990) CEPCI = 357.6 basis.

Unit	Installed cost	Additional notes
2 Centrifugal pumps	\$16,000	Including drives
Process heater	\$37,000	
Distillation column	\$227,500	field erected, including internals
Agitated tank	\$39,000	
CS/SS heat exchanger	\$53,600	
CS heat exchanger	\$50,500	
Total purchased equipment:	**\$196,100**	All units except column
Freight, taxes, insurance	\$23,500	12%: according to Guthrie[78]
Total delivered equipment:	**\$196,100**	Include freight, taxes and insurance
Total field erected equipment:	**\$227,500**	Distillation column

Equations B.11 to B.13 are applied to finish the estimate. The values of factors are not repeated and may be found in chapter 3.2.2. The set for fluid processes is applied, this set is rigid and does not need any argumentation. Only the value for land is omitted for the case study states no extra land acquirement is necessary.

Note that in the calculation of the total depreciable capital in table B.9 the field erected price of the column is included with the delivered equipment to site. This is in accordance with the instruction supplied by Peters and Timmerhaus.

$$C_{\mathrm{DPC}} = (1 + F_{\mathrm{IL}} + F_{\mathrm{I}} + F_{\mathrm{P}} + F_{\mathrm{E}} + F_{\mathrm{B}} + F_{\mathrm{Y}} + +F_{\mathrm{F}} + F_{\mathrm{L}}) \cdot \sum_{k=1}^{n} E_{\mathrm{k}} \tag{B.11}$$

$$C_{\mathrm{DIC}} = C_{\mathrm{DPC}} + (1 + F_{\mathrm{E\&S}} + F_{\mathrm{CE}}) \cdot \sum_{k=1}^{n} E_{\mathrm{k}} \tag{B.12}$$

$$C_{\mathrm{TDC+land}} = (1 + F_{\mathrm{CF=5\%}} + F_{\mathrm{C=10\%}}) \cdot C_{\mathrm{DIC}} \tag{B.13}$$

Table B.9: The method of Peters and Timmerhaus[14] applied. The value of the factors may be found on page 23. Delivered equipment includes the field erected column.

Cost item	Price
Delivered equipment	**$447,100**
Equipment installation labour *IL*	$210,100
Instrumentation and controls *I*	$80,500
Piping *P*	$295,100
Electrical installations *E*	$49,200
Buildings *B*	$80,500
Yard improvements *Y*	$44,700
Service facilities *F*	$313,000
Land *L*	-
Direct plant cost	**$1,520,200**
Engineering and supervision *E&S*	$147,500
Construction expenses *CE*	$183,300
Direct and indirect costs	**$1,851,000**
Contractor's fee *CF*	$93,900
Contingency *C*	$187,800
Total depreciable costs	**$2,132,700**

B.6 A. Bejan, G. Tsatsaronis & M. Moran

Equations B.14 and B.15 show that the approach by Bejan, Tsatsaronis and Moran[64] is similar to Lang's. The equipment price is on a F.O.B. basis extracted from Peters and Timmerhaus[13] (see previous example) and includes the field erected column. The chosen factor was developed for site expansion by the authors leading to a final estimate of $1,198,800 in 1990, 357.6 is the CEPCI value.

$$C_{\mathrm{TDC}} = F_{\mathrm{TDC}} \cdot \sum_{k=1}^{n} E_{\mathrm{k}} \tag{B.14}$$

$$C_{\mathrm{TDC}} = 2.83 \cdot \$423,600 = \mathbf{\$1{,}198{,}800} \tag{B.15}$$

B.7 A.Z. Marouli, Z.B. Maroulis & G.D. Saravacos

An example of this method is not included in this section. The factors listed in the publications[65][66] are linked to specific process within the food industry and are not successfully employed in this environment. The factors are employed similarly to Lang's or like Bejan et al. as displayed above.

B.8 N.G. Bach

The estimate for equipment pieces from Guthrie[79] (section C.7) is adopted in this example for Bach[67] did not include a cost database. The basis should be delivered to site, equally as in section B.4 the costs are based on the inclusion of freight, taxes and insurance. At CEPCI 125.7 (1970) the field erected column and the delivered equipment are added to find \$248,800. This is not entirely correct for installation cost is already included in the field erected cost and also within the factor.

Bach provides us with a battery limit investment method, discriminating Lang factors between process units (PU), utilities and storage and handling. Since storage and handling is not set in the case study and a cooling tower price on delivered basis is not found in literature, these two are neglected. Merely an investment for the process units is determined via equations B.16 to B.18. It is considered a process unit rather than an alteration, which would cause the factor to be different, because the proposed expansion is closely interconnected. The average value for process units (3.13) is increased by 0.29, to account for the high instrumentation needs of the plant. This is the highest value found in Bach's results.

$$C_{\text{BL direct}} = C_{\text{PU}} + C_{\text{U}} + C_{\text{S\&H}} + C_{\text{A/A}} \tag{B.16}$$

$$C_{\text{PU}} = F_{\text{PU}} \cdot \left[\sum_{k=1}^{n} E_{\text{k}}\right]_{\text{PU}} \tag{B.17}$$

$$C_{\text{BL direct}} = 3.42 \cdot \$248,800 = \mathbf{\$850,900} \tag{B.18}$$

The more thorough method by Bach could also be employed in which other elements are also case specific. Possible values are indicated in figure F.1 in chapter 3.2.3. However more detailed information on the design is to be known to the estimator to actually expect an increase in accuracy by performing such an estimate. Note that the final estimate merely takes the direct costs within battery limits into account.

B.9 C.A. Miller

The equations (B.19 to B.21) provided by Miller[68] to estimate the direct costs within battery limits and the total direct plant cost are shown below.

$$C_{\text{BE}} = F_{\text{MUE}} \cdot \sum_{k=1}^{n} E_{\text{k}} \tag{B.19}$$

$$C_{\text{BL direct}} = (1 + F_{\text{IL}} + F_{\text{SU}} + F_{\text{P}} + F_{\text{I/L-E}} + F_{\text{I/L-P}} + F_{\text{E}} + F_{\text{I}} + F_{\text{M}} + F_{\text{B}}) \cdot C_{\text{BE}} \tag{B.20}$$

$$C_{\text{DPC}} = (1 + F_{\text{S\&H}} + F_{\text{U}} + F_{\text{S}}) \cdot C_{\text{BL direct}} \tag{B.21}$$

The first step is to convert the average main plant item cost in a 1958 (CEPCI = 99.7) dollar value. The same estimate from Chilton (see page 90) is taken and converted to give \$141,700 in 1958 for 7 plant items delivered to site of which the process heater is field erected. Miller subtracts sales tax however this was a low number (+/- 3%) in his time. It is neglected in this estimate for it unnecessarily complicated the procedure by adding it at the end. This leads to \$20,200 as the average main plant item cost is, indicating which set of Miller's factors to apply, which is a function of average plant item cost.

Table B.10: Factor values selected From Miller[68] and the argumentation for the choice. Values are indicated as follows: Low/Probable/High.

Factor	Values	Argumentation
MUE	0.10/0.10/0.10	Average
IL	0.09/0.10/0.12	Average, in the calculation is does not work on the field erected furnace
SU	0.07/0.08/0.09	Heavy equipment, mostly carbon steel
P	0.17/0.20/0.25	Fluid plants
I/L-E	0.03/0.04/0.05	Some alloys, high temperatures
I/L-P	0.03/0.04/0.05	Some alloys, high temperatures
E	0.04/0.05/0.06	High average unit cost, few heavy drives
I	0.16/0.18/0.20	Maximum instrumentation and control
M	0.02/0.03/0.04	Average
B	0.04/0.08/0.12	Outdoor construction, large range of possibilities
-	*0.40/0.45/0.60*	*Services, as fraction of B*
S&H	0.02/0.04/0.06	Average, additions to existing site
U	0.02/0.03/0.06	Low, additions to existing site
S	-/0.01/0.02	Low, additions to existing site

Table B.11: Computation of low, probable and high values of directs costs of the case study project based on the factors from table B.11.

Cost item	**Price**		
	Low	*Probable*	*High*
Main plant items	**$127,500**	**$141,700**	**$155,900**
Miscellaneous unlisted equipment	$12,800	$14,200	$15,600
Basic equipment	**$140,300**	**$155,900**	**$171,500**
Field erection	$5,900	$6,600	$7,900
Foundations and supports	$9,800	$12,500	$15,400
Piping	$23,900	$31,200	$42,900
Insulation equipment	$4,200	$6,200	$8,600
Insulation piping	$4,200	$6,200	$8,600
Electrical	$5,600	$7,800	$10,300
Instrumentation	$22,400	$28,100	$34,300
Miscellaneous	$2,800	$4,700	$6,900
Buildings	$5,600	$12,500	$20,600
Building services	$2,200	$5,600	$12,400
Battery limits - direct	**$226,900**	**$277,300**	**$339,400**
Storage and handling	$4,500	$11,100	$20,400
Utilities	$4,500	$8,300	$20,400
Services	-	$2,800	$6,800
Direct plant cost	**$235,900**	**$299,500**	**$387,000**

Table B.10 shows the factor values for each cost item, these are worked out in table B.11. Each factor gets a low, probable and high value assigned to it as proposed by Miller. This delivers a range of answers with a most probable answer. The accuracy of this range is highly dependent on project definition and estimator experience. The final estimates for both battery limits and the total expansion do not include any indirect costs.

B.10 J. Happel & D.G. Jordan

For the computation by Happel and Jordan[69] the database of Guthrie[79] is employed, see chapter C.7. Happel and Jordan's method needs installed equipment cost including instrumentation. Therefore the installation (plus freight) and instrumentation cost determined on page 107 is added to add showing an investment of $289,000 in 1970 dollar value (CEPCI = 125,7). Then equation B.22 and B.23 are applied to find the battery limit investment. Since the factor values are of a very small range (see chapter 3.2.3), mostly the average values are taken and summed in table B.12. Only the piping factor value is taken as the high value (0.50) as advised by Happel and Jordan for fluid processes. No special equipment is included in the case study.

$$C_{\text{physical}} = C_{\text{special}} + (1 + F_{\text{I/L}} + F_{\text{P}} + F_{\text{FO}} + F_{\text{B}} + F_{\text{S}} + F_{\text{FP}} + F_{\text{E}} + F_{\text{PA}}) \cdot \sum_{k=1}^{n} E_{\text{k}} \quad \text{(B.22)}$$

$$C_{\text{BL}} = (1 + F_{\text{E\&C}}) \cdot (1 + F_{\text{CF}} + F_{\text{C}}) \cdot C_{\text{physical}} \quad \text{(B.23)}$$

Table B.12: The battery limit estimate performed by the method of Happel and Jordan[69] in 1970 (CEPCI = 125.7) values.

Cost item	**Price**		
	Material	*Labour*	*Total*
Installed equipment			**$289,000**
Insulation	$21,700	$32,600	$54,300
Piping	$144,500	$144,500	$289,000
Foundations	$11,600	$17,400	$29,000
Buildings	$11,600	$8,100	$19,700
Support structures	$11,600	$2,300	$13,900
Fireproofing	$2,200	$14,300	$16,500
Electrical	$13,000	$19,500	$32,500
Paint and clean-up	$2,200	$14,300	$16,500
Physical cost	**$218,400**	**$253,000**	**$471,400**
Engineering and construction			$141,400
Contractor's fee			$61,300
Contingency			$61,300
Battery limits			$735,400

B.11 J. Cran

The equations employed by Cran[60] are shown below in equation B.24 and B.25. His equations are most useful for battery limit investment estimates and therefore the off-sites are neglected and set at \$0. As an input the database of Guthrie[79] is applied and converted to delivered equipment to site as shown before in section B.4.

The battery limit factor for fluids is selected and applied, including the standard deviation analysis. The final estimate format is an average value for the battery limit investment in 1970 dollar value (CEPCI = 125.7) with a range of 95% certainty.

$$C_{\mathrm{TDC}} \;=\; C_{\mathrm{O}} \;+\; F_{\mathrm{BL}} \;\cdot\; \sum_{k=1}^{n} E_{\mathrm{k}} \tag{B.24}$$

$$C_{\mathrm{BL}} \;=\; \$0 \;+\; 3.15 \pm 0.81 \;\cdot\; \$248,800 \;=\; \mathbf{\$783{,}700} \;\pm\; \mathbf{\$201{,}500} \tag{B.25}$$

B.12 J.H. Hirsch & E.M. Glazier

The input of into Hirsch and Glazier's[71] method should be close to the development data (1958) because of the calibrated equations, see B.26 to B.29. Therefore Aries's[12] database is adopted, which is fairly close in time with 86.1 as the CEPCI value. The calculations of the equipment price was performed in section B.3. However the method by Hirsch and Glazier has the carbon steel base price as an input on which the factors work, and assigns the extra costs for alloys as incremental costs. These prices for carbon steel equipment are shown in table B.13.

Table B.13: Calculating incremental alloy cost from Aries and Newton[12]. All prices are shown as 1954 (CEPCI = 86.1) prices. * The furnace price is from Chilton[40].

Unit	**Purchased cost**	**Additional notes**
2 Centrifugal pumps	\$1,500	Including drives
Process heater	\$65,300*	From Chilton[40], installed price
Distillation column	\$15,900	\$610 per tray
Agitated tank	\$10,500	Merely based on vessel volume and not on agitator
CS/SS heat exchanger	\$9,100	
CS heat exchanger	\$15,000	Slightly out of range, extrapolated
Total CS basis:	**\$117,300**	
Total including alloys:	\$153,600	See page 92
Incremental alloy cost	**\$36,300**	

$$C_{\mathrm{BL}} \;=\; F_{\mathrm{IDC}} \;\cdot\; \Big[(1 + F_{\mathrm{IL}} + F_{\mathrm{P}} + F_{\mathrm{AM}}) \;\cdot\; \sum_{k=1}^{n} (E_{\mathrm{k}}) + \sum_{k=1}^{n} (C_{\mathrm{alloy,k}}) + C_{\mathrm{erected}}\Big] \tag{B.26}$$

$$F_{\mathrm{IL}} \;= 0.635 - \frac{0.992 \cdot hex}{\sum_{k=1}^{n} E_{\mathrm{k}}} + \frac{0.506 \cdot ffv}{\sum_{k=1}^{n} E_{\mathrm{k}}} - 0.154 \cdot \log \frac{\sum_{k=1}^{n} E_{\mathrm{k}}}{1,000,000} \tag{B.27}$$

$$F_{\mathrm{P}} = 0.266 - \frac{0.156 \cdot hex}{\sum_{k=1}^{n} E_{\mathrm{k}}} + \frac{0.556 \cdot pd}{\sum_{k=1}^{n} E_{\mathrm{k}}} - 0.014 \cdot \log \frac{\sum_{k=1}^{n} E_{\mathrm{k}}}{1,000,000} \quad \text{(B.28)}$$

$$F_{\mathrm{AM}} = 0.334 + \frac{1.194 \cdot ts}{\sum_{k=1}^{n} E_{\mathrm{k}}} + 0.033 \cdot \log \frac{\sum_{k=1}^{n} E_{\mathrm{k}}}{1,000,000} \quad \text{(B.29)}$$

This leads to table B.14 showing the computations of the factors. The incremental alloy cost is known and the erected cost item is zero. When all are implemented into equation B.26, the final estimate for the battery limit investment may be computed: **$491,300**.

Table B.14: The parameter values of Hirsch and Glazier's[71] equations.

Factor/Unit	Value	Additional notes
hex	$24,100	21% of equipment mix
ffv	$65,300	56% of equipment mix
pd	$1,500	1% of equipment mix
ts	$26,400	23% of equipment mix
F_{IL}	0.86	
F_{P}	0.25	
F_{AM}	0.57	
F_{IDC}	1.40	Set value by Hirsch and Glazier[71]

B.13 H.P. Loh, J. Lyons & C.W. White

The database from Loh et al.[72] is applied on the case study to find the result of table B.15. A base price is gained from their cost curves together with installation percentages and materials of construction (MOC) adjustment factors to find the total installed equipment cost.

Table B.15: Computation of the installed equipment price by Loh et al.[72], CEPCI = 389.5 (1998). Note that the correlation for the vessel was out of range.

Unit	CS base price	Installation	MOC	Installed price
2 centrifugal pumps	$11,000	$2,800	-	$13,800
Process heater	$370,000	$111,000	-	$481,000
Distillation column	$100,000	$30,000	$190,000	$320,000
Vessel	$52,000	$10,400	-	$62,400
Agitator	$47,000	$9,400	-	$56,400
Heat Exchanger CS/SS	$46,000	$9,200	$30,800	$86,000
Heat Exchanger CS	$95,000	$19,000	-	$114,000
Total installed:				**$1,133,600**

The formula for finding the battery limit direct costs is given in equation B.30. It is worked out in tabular form in table B.16. The values are to be found in appendix J, the column for liquid systems is applied. In particular for highw pressure systems, for on average the pressure is higher than 10 bar.

$$C_{\text{physical}} = (1+F_{\text{FO}}+F_{\text{SU}}+F_{\text{B}}+F_{\text{I/L}}+F_{\text{I}}+F_{\text{E}}+F_{\text{P}}+F_{\text{PA}}+F_{\text{M}})\cdot\sum_{k=1}^{n}(1+F_{\text{MOC}}+F_{\text{IL}})\cdot E_{\text{k}} \tag{B.30}$$

Table B.16: The battery limit estimate for direct costs estimated by the method of Loh et al.[72], prices are in 1970 dollar (CEPCI = 389.5) values.

Cost item		**Price**	
	Material	*Labour*	*Total*
Installed equipment			**$1,133,600**
Foundations	$68,000	$90,400	$158,400
Structural Steel	$56,700	$28,400	$85,100
Buildings	$34,000	$34,000	$68,000
Insulation	$34,000	$51,000	$85,000
Instruments	$79,400	$31,800	$111,200
Electrical	$102,000	$76,500	$178,500
Piping	$396,800	$198,400	$595,200
Painting	$5,700	$17,100	$22,800
Miscellaneous	$56,700	$45,400	$102,100
Battery limit direct	$833,300	$573,000	**$1,406,300**

Appendix C

Examples: Factorial Techniques - Hand Type

The following appendix section contains the worked out examples for the Hand type methods explained in chapter 3.3. The same hypothetical case study as for the Lang examples is applied, see appendix B for more information on the case. This section's purpose is mainly to clarify the ways of applying each capital cost estimation technique. However the results are also compared briefly in chapter 4.1. Depending on the accessible information each method is worked out as much as possible. Only CEPCI is adopted as the measure of indexing because it is most general and extends back to the 1940's. Separate indexing per equipment type would also be a possibility however is considered to be too tedious and unnecessary for the applied ranges are small.

C.1 W.E. Hand

The Hand[73] method is applied following equation C.1, leading to table C.1 which shows the final result in 1958 dollar value. The F.O.B. price of equipment pieces is determined by applying the rules of thumb provided in Hand's original article (not taking into account alloys). The costs incorporated in the factor may be split out over cost items in line with table 3.13 on page 36.

$$C_{\mathrm{BL}} = \sum_{k=1}^{n} F_{\mathrm{k}} \cdot E_{\mathrm{k}} \tag{C.1}$$

Table C.1: The battery limit estimate estimated by the method of Hand[73], prices are in 1958 dollar (CEPCI = 99.7) values.

Equipment Item	**F.O.B. Price**	**Factor**	**Installed Price**
2 Pumps	\$8,400	4.0	\$33,500
Process heater	\$70,700	2.0	\$141,400
Column	\$42,900	4.0	\$171,500
Agitated vessel	\$12,200	4.0	\$48,800
2 Heat exchangers	\$7,400	3.5	\$25,900
Instruments	\$28,800	4.0	\$115,200
BL investment	**\$170,400**		**\$536,300**
+ Contingency (15%)			**\$616,700**

C.2 W.F. Wroth

The method of Wroth[74] is similar to Hand's[73] method worked out above. The method works in the same line, see equation C.1, but with different factors. The result is visible in table C.2, in which the factor for pumps is the average between pumps and drives, the latter is included in the pump price. The F.O.B. price is taken from Hand's method, for Wroth provides no equipment price data.

Table C.2: The battery limit estimate estimated by the method of Wroth[74], prices are in 1958 dollar (CEPCI = 99.7) values.

Equipment Item	**F.O.B. Price**	**Factor**	**Installed Price**
2 Pumps	$8,400	7.8	$65,100
Process heater	$70,700	2.0	$141,400
Column	$42,900	4.0	$171,600
Agitated vessel	$12,200	4.1	$50,000
2 Heat exchangers	$7,400	4.8	$35,500
Instruments	$28,800	4.1	$118,100
BL investment	**$170,400**		**$581,700**
+ Contingency (15%)			**$669,000**

C.3 J. Cran

Equations C.2 to C.4 show the workings of Cran's[60] Hand type factorial method. A key feature is the fact that instruments are costed separately, which actually also occurred in the original Hand[73] type methods, but may others deviated from. The final estimate is merely an estimate for the direct costs within battery limits for the estimation of indirect costs is not included in Cran's factors and no additional way was provided. Therefore equation C.4 is not executed, but merely the result of equations C.2 and C.3 were summed.

$$E_{\mathrm{T,direct}} = \sum_{k=1}^{n} F_{\mathrm{k}} \cdot E_{\mathrm{k}} \tag{C.2}$$

$$I_{\mathrm{T,direct}} = F_{\mathrm{I}} \cdot \sum_{i=1}^{n} I_{\mathrm{i}} \tag{C.3}$$

$$C_{\mathrm{BL}} = (E_{\mathrm{T}} + I_{\mathrm{T}}) \cdot (1 + F_{\mathrm{indirect}}) \tag{C.4}$$

Since Cran did not include a cost database in his article, the values from Guthrie[78][79] are adopted, see appendix C.7. Instruments cost was extracted from Cran's paper. This leads to the computations made in table C.3.

Table C.3: Direct battery limit cost calculated with the factors of Cran[60] and the equipment database of Guthrie[78][79] in 1970 dollar values(CEPCI = 125.7) values.

Equipment Item	F.O.B. Price	Factor	Installed Price
2 Pumps	\$17,400	2.8	\$48,700
Process heater	\$107,100	1.3	\$139,200
Column	\$71,500	2.1	\$150,200
Vessel	\$18,500	2.3	\$42,600
Agitator	\$2,500	1.3	\$3,300
Heat exchangers (SS)	\$8,500	2.1	\$17,900
Heat exchangers (CS)	\$8,100	1.7	\$13,800
Equipment total			\$415,700
Instruments	\$16,400	2.5	\$41,000
BL direct cost			**\$581,700**

C.4 T.R. Brown

Brown[76][77] is an adaptation of various methods. In this example it is chosen to use Garrett's[81] database and factors, see chapter C.9. The material of construction factor f_{MOC} is dependent on the alloy ratio as explained on page 39. Equation C.5 is employed to find the total depreciable cost for the example case project. It is worked out in table C.4.

$$C_{\text{TDC}} = F_{\text{I}} \cdot F_{\text{B}} \cdot \sum_{k=1}^{n} (F_{\text{H,k}} \cdot f_{\text{MOC,k}} \cdot E_{\text{k}}) \tag{C.5}$$

Table C.4: Computation of the total depreciable capital employing Brown's[76][77] method and Garrett's[81] database and factors. All values are denoted in CEPCI = 320.

Equipment Item	F.O.B. Price	Factor	Alloy ratio	f_{MOC}	Installed Price
2 Pumps	\$17,200	1.5	1	1	\$25,800
Process heater	\$270,000	2.1	1	1	\$567,000
Column (SS)	\$111,700	4.16	2.1	0.68	\$315,900
Trays (SS)	\$29,500	1.2	1.9	0.72	\$25,400
Agitated vessel	\$36,000	2.5	1	1	\$90,000
Heat exchangers (SS)	\$22,900	3.2	2.3	0.65	\$47,600
Heat exchangers (CS)	\$18,700	3.2	1	1	\$59,800
Equipment total					**\$1,131,500**
Instrument factor (45%)					x 1.45
Buiding factor (6%)					x 1.06
TDC					**\$1,739,100**

C.5 D.R. Woods

The worked out example for Woods'[44] method is examined next. Equation C.6 to C.9 reflect the computational system. Because the off-sites and buildings are neglected in this case, the final estimate called total module (TM) is replaced by a battery limit estimate.

$$C_{\text{BL-L\&M}} = C_{\text{I}} + C_{\text{B}} + \sum_{k=1}^{n} \left(F_{\text{L\&M*,k}} \cdot f_{\text{MOC,k}} \cdot E_{\text{k}}\right) \quad \text{(C.6)}$$

$$C_{\text{BL-PM}} = C_{\text{BL-L\&M}} + C_{\text{TFI}} \quad \text{(C.7)}$$

$$C_{\text{BM}} = C_{\text{BL-PM}} + C_{\text{O}} + C_{\text{E\&C}} \quad \text{(C.8)}$$

$$C_{\text{TM}} = C_{\text{CF}} + C_{\text{C1}} + C_{\text{C2}} \quad \text{(C.9)}$$

The equational system is displayed in tabular form in table C.5. Note that the tray column's material of construction factor is 1 despite the fact it is made out of stainless steel. The reason is the fact that the L+M* factor in this case is already mend to work on stainless steel equipment and thus does not have to be adapted.

Table C.5: Woods[44] database, factors and methods applied on the example case, CEPCI = 1,000

Equipment Item	F.O.B. Price	L+M*	f_{MOC}	Installed price	Instruments	Total
2 Pumps	$32,200	1.47	1	$47,300	$14,000	$61,300
Process heater	$1,250,300	1.3	1	$1,625,400	$63,000	$1,688,400
Tray column (SS)	$650,300	1.78	1	$1,157,500	$150,000	$1,307,500
Agitated vessel	$166,600	2.48	1	$413,200	$17,400	$430,600
Heat exchangers (SS)	$152,700	2.5	0.62	$235,100	$27,000	$262,100
Heat exchangers (CS)	$292,700	2.5	1	$731,800	$27,000	$758,800
Equipment total						**$4,508,700**
Tax, freight, insurance (20% of F.O.B.)						$509,000
BL physical cost						**$5,017,700**
Engineering & construction (28% of L+M*)						$458,000
BM BL cost						**$5,475,700**
Contractor's fee (4% of BM)						$219,000
Contingencies for delays (12.5% of BM)						$684,500
Contingencies for scope change (20% of BM)						$1,095,100
total BL investment						**$7,474,300**

C.6 J.R. Couper, W.R. Penney, J.R. Fair & S.M. Walas

The method employed by Couper et al.[47] is identical to Cran's[60] in appendix C.3 except for the database behind it. The result is tabulated in table C.6. The instrument cost is adopted from Cran, the other prices are from Couper et al. shown in 2012 prices.

Table C.6: Direct battery limit cost calculated with the factors of Cran[60] and the equipment database of Couper et al.[47] in 2012 dollar values(CEPCI = 521.9) values.

Equipment Item	F.O.B. Price	Factor	Installed Price
2 Pumps	$9,100	2.8	$25,500
Process heater	$411,900	1.3	$535,500
Column	$275,300	2.1	$578,100
Vessel	$105,200	2.3	$242,000
Agitator	$30,400	1.3	$39,500
Heat exchangers (SS)	$140,000	2.1	$294,000
Heat exchangers (CS)	$126,900	1.7	$215,700
Equipment total			**$1,930,300**
Instruments	$68,200	2.5	$170,500
BL direct cost			**$2,100,800**

C.7 K.M. Guthrie

Since the information provided in the case study is by far not enough to make an estimation of costs outside of battery limits using Guthrie's[78][79] method, merely a battery limit estimate is computed. Wiping out all all categories from equation C.10 except for the process unit part, delivers equation C.11.

$$C_{\text{TDC}} = C_{\text{CP-TM}} + C_{\text{OU-TM}} + (C_{\text{OP}} + C_{\text{B}} + C_{\text{Y}}) \cdot F_{\text{indirect}} \qquad \text{(C.10)}$$

$$C_{\text{CP-TM}} = \sum_{k=1}^{n} (F_{\text{indirect,k}} \cdot (F_{\text{M,k}} + F_{\text{L,k}}) + f_{\text{D,k}} + f_{\text{P,k}} + f_{\text{MOC,k}} + ...) \cdot E_{\text{k}} \qquad \text{(C.11)}$$

Table C.7 shows a simplified version of Guthrie's estimation scheme. The base cost is the one upon which the factors are factors are applied, the F.O.B. cost is merely for the administration and does contain incremental cost for alloy usage, pressure factors, type factors etc, but not materials and labour. These may be computed separately per material type, however are not shown in the table. For example the base price for the distillation column is relatively low to the F.O.B. cost, because of the incremental cost due to stainless steel usage. Therefore the factors work on the base price and causing the total installed price to be relatively close to the F.O.B. price.

Table C.7: The cost estimate performed with Guthrie's[78][79] factors in 1970 dollar values (CEPCI = 125.7) values.

Equipment Item	Base price	F.O.B. price	Installed cost
2 Pumps	$12,400	$17,400	$45,700
Process heater	$105,100	$107,100	$225,800
Column (SS)	$18,800	$71,500	$130,400
Agitated Vessel	$21,000	$23,800	$89,700
Heat exchanger (SS)	$4,000	$8,500	$17,200
Heat exchanger (CS)	$7,400	$8,100	$24,000
Equipment total			**$532,800**
Contingency and contractor's fee (18%)			$96,000
BL direct cost			**$628,800**

C.8 G.D. Ulrich

Ulrich[80] has provided a manner to more easily convert Guthrie's[78][79] estimate to a full estimate without going into too much details. The governing equation is shown in equation C.12, and worked out in equation C.13, including the estimate made in the previous appendix. The resulting total depreciable capital cost is estimated at $792,300 in 1970 dollar value, CEPCI = 125.7. These are calculated with the average values from Ulrich.

$$C_{\text{TDC}} \;=\; C_{\text{CP-TM}} \;\cdot\; (1 + F_{\text{Y}} + F_{\text{B}} + F_{\text{O}}) \tag{C.12}$$

$$C_{\text{TDC}} \;=\; \$628,800 \;\cdot\; (1 + 0.05 + 0.04 + 0.017) \;=\; \$792,300 \tag{C.13}$$

C.9 D.E. Garrett

Garrett's[81] system has already been shown in Brown's[76][77] section in appendix C.4, for Brown is an extension of Garrett. For clarity what part belong's to Garrett and what part to Brown, Garrett's method is worked out in table C.8. Note how the factors work on the base price, instead on the F.O.B. price, the latter including incremental alloy and pressure cost factors.

Table C.8: Computation of the total depreciable capital Garrett's[81] database and factors. All values are denoted in CEPCI = 320.

Equipment Item	Base Price	F.O.B. Price	Factor	Installed Price
2 Pumps	$17,200	$17,200	1.5	$25,800
Process heater	$270,000	$270,000	2.1	$567,000
Column (SS)	$38,000	$111,700	4.16	$158,100
Trays (SS)	$15,500	$29,500	1.2	$18,600
Agitated vessel	$36,000	$36,000	2.5	$90,000
Heat exchangers (SS)	$9,800	$22,900	3.2	$47,600
Heat exchangers (CS)	$18,700	$18,700	3.2	$59,800
BL investment				**$1,131,500**

C.10 I.V. Klumpar & S.T. Slavsky

The method by Klumpar and Slavsky[82][83][84][85] is too detailed to be fully displayed here. Each material category (concrete, piping, steel, instruments, insulation, electrical and paint) is costed seperately. The installation labour of the equipment and each material category is costed seperately accordingly leading to a very large table not providing much insight into the method. The set of formula's displayed in equation C.14 to C.16 and explained in chapter 3.3.4 are best explained by reading the original articles.

$$C_{\mathrm{BL}} = \sum_{k=1}^{n} E_{\mathrm{k}} \cdot (1 + F_{\mathrm{SMC,k}}) + C_{\mathrm{IL,k}} + C_{\mathrm{SLC,k}} \tag{C.14}$$

$$C_{\mathrm{IL,k}} = F_{\mathrm{IL}} \cdot \eta_{\mathrm{IL,k}} \cdot W_{\mathrm{IL}} \cdot E_{\mathrm{k}} \tag{C.15}$$

$$C_{\mathrm{SLC,k}} = \sum_{i=1}^{n} F_{\mathrm{i,k}} \cdot \eta_{\mathrm{i}} \cdot W_{\mathrm{i}} \cdot E_{\mathrm{k}} \tag{C.16}$$

For working out of the case study the F.O.B. equipment prices from Guthrie[78][79] were adopted. Applying the factors given in Klumpar and Slavsky's articles for materials and labour provides the material cost per equipment piece and manhours per equipment piece and profession accordingly. Applying the manhour rates shown in table C.10, factors by Klumpar and Slavsky results in the final estimate shown in table C.9.

Table C.9: The battery limit investment estimation scheme by Klumpar and Slavsky[82][83][84][85] based upon the F.O.B. equipment values from Guthrie[78][79]. Dollar values are shown in 1984 values (CEPCI = 322.6)

Equipment pieces	**Equipment F.O.B.**	**Materials**	**Labour**	**Total**
2 Pumps	$44,700	$29,000	$7,600	$81,300
Process heater	$274,900	$90,300	$78,400	$443,600
Distillation column (SS)	$183,500	$189,000	$48,600	$421,100
Agitator	$6,400	$1,900	$200	$8,500
Vessel	$47,500	$51,400	$8,000	$106,900
Heat exchangers (SS)	$21,800	$17,200	$2,900	$41,900
Heat exchangers (CS)	$20,800	$16,500	$2,700	$40,000
BL physical cost	**599,600**	**395,300**	**148,400**	**1,143,300**
Freight (7% of BL physical)				$80,000
Other directs (6% of BL physical)				$68,600
BL direct cost				**1,291,900**
Field personnel (73% of labour)				$108,300
Other field indirect (130% of labour)				$192,900
BL construction cost				**1,593,100**
Home office (17% of construction cost)				$270,800
Project management (8% of construction cost)				$127,400
Owner's cost (5% of construction cost)				$79,700
total BL investment				**2,071,000**

Table C.10: The salary rates per profession applied in working out the example, noted as 1984 U.S. dollar values (CEPCI = 322.6)

Profession	**Wage [$/manhour]**
Installation labour	$12.18
Concrete pouring	$11.15
Pipe fitting	$13.16
Steel working	$12.56
Instrument installation	$13.50
Insulation labour	$10.71
Electrical installation	$13.95
Painting	$10.17

C.11 A.M. Gerrard, D.J. Brennan & K.A. Golonka

The method by Gerrard[15] and Brennan and Golonka[86], better known as the IChemE method is applied on the case study. The database of Garrett[81] was adopted to estimate the F.O.B. cost. Equation C.17 and C.18 are employed to find the battery limit cost.

$$C_{\text{DPC}} = \sum_{k=1}^{n} E_{\text{k}} + E_{\text{CS,k}} \cdot (F_{\text{IL,k}} + F_{\text{P,k}} + F_{\text{I,k}} + F_{\text{E,k}} + F_{\text{B,k}} + F_{\text{CV,k}} + F_{\text{I/L,k}}) \quad \text{(C.17)}$$

$$C_{\text{BL}} = (1 + F_{\text{E\&S}} + F_{\text{MO}} + F_{\text{C}} + F_{\text{CF}}) \cdot C_{\text{DPC}} \quad \text{(C.18)}$$

In order to apply the IChemE method the carbon steel price of each equipment piece in 2000 £pound sterling needs to be determined, as done in table C.11. That value, type of process, type of construction project, environment, equipment type and more determines the factor value for that individual piece of equipment. These conditions are to be read in the original paper/book Gerrard, Brennan and Golonka. The table therefore shows that factors are low for high value equipment and high for low value equipment.

Table C.11: Scheme of applying the IChemE method. Dollar values are shown in CEPCI = 320 values based on the F.O.B. equipment price of Garrett's[81] database.

Equipment pieces	**Equipment F.O.B.**	**Calculation price [$]**	**Calculation price [2000 £]**	**Computed factor**	**Installed price [$]**
2 Pumps	$17,200	$17,200	£5,300	2.99	$92,700
Process heater	$270,000	$270,000	£166,000	0.81	$558,900
Distillation column (SS)	$141,200	$82,700	£50,900	1.81	$364,600
Agitated tank	$36,000	$36,000	£22,100	1.99	$131,400
Heat exchangers (SS)	$22,900	$9,800	£9,800	2.70	$81,400
Heat exchangers (CS)	$18,700	$18,700	£18,700	1.88	$72,200
Direct plant cost					**$1,301,200**
Engineering & supervision (15% of DPC)					$195,200
Management overhead (10% of DPC)					$130,100
Contingencies (15% of DPC)					$195,200
Contractor fee's (5% of DPC)					$65,100
Total BL investment					**$1,886,800**

C.12 A.Chauval, G. Fournier & C. Raimbault

The system presented by Chauval et al.[61] is very similar to Guthrie's[78][79] for process units. The governing formula is shown in equation C.19 and worked out in table C.12

$$C_{\text{BL}} = \sum_{k=1}^{n} E_{\text{k}} \cdot (F_{\text{k}} + f_{1,\text{k}} \cdot f_{2,\text{k}} \cdot f_{3,\text{k}} \cdot f_{\ldots,\text{k}}) \tag{C.19}$$

Table C.12: The cost estimate performed with Chauval et al.[61] database and factors in 2003 dollar values (CEPCI = 394.1).

Equipment Item	Base price	F.O.B. price	Installed cost
2 Pumps	\$35,000	\$40,200	\$109,400
Process heater	\$330,000	\$330,000	\$788,700
Column (SS)	\$103,100	\$208,200	\$425,100
Vessel	\$110,200	\$126,700	\$344,900
Agitator	\$58,000	\$58,000	\$107,300
Heat exchanger (SS)	\$55,000	\$121,000	\$243,300
Heat exchanger (CS)	\$135,000	\$144,500	\$444,400
Equipment total			**\$2,463,100**
Contingency and contractor's fee (18%)			\$443,400
BL direct cost			**\$2,906,500**

C.13 W.D. Seider, J.D. Seader, D.R. Lewin & S. Widagdo

The publication by Seider et al.[17] merely contains a database and applies factors from other methods to complete the factorial estimate. Therefore the method is not worked out here, it may merely provide an F.O.B. equipment price. For the comparison made in chapter 4.1 and appendix D Guthrie's[78][79] factors were applied to come to a full cost scheme.

C.14 R. Sinnott & G. Towler

The same notes regarding cost databases and factors made in the section on Seider et al.[17] above, apply to here. Sinnott and Towler[46] also merely provide equipment F.O.B. costs.

C.15 R. Turton, R.C. Bailie, W.B. Whiting & J.A. Shaeiwitz

The method by Turton et al.[45] is somewhat inscrutable for the base costs is calculated following equation C.20, pressure factors are computed in a similar fashion. Material factors are sometimes tabulated and sometimes included in the installation factors, depending on the type of equipment. The structure of applying factors is also equipment type dependent. Therefore laying out the structure in this example is fuzzy, for it's highly algorithmic nature. To simplify only the base price and final installed costs are presented in table C.13. The intermediate cost structure is virtually impossible to determine in Turton et al.'s method, the factorial technique is only focussed on finding the final battery limit estimate.

$$\log_{10} E = K_1 + K_2 \cdot \log_{10} S + K_3 \cdot (\log_{10} S)^2 \tag{C.20}$$

Table C.13: The computed estimate case study result performed with Turton et al's.[45] method, values are shown in CEPCI = 397.0 values corresponding to 2008.

Equipment Item	**Base price**	**Installed price**
2 Pumps	$17,200	$59,700
Process heater	$689,100	$1,714,200
Column (SS)	$24,500	$437,500
Trays (SS)	$33,800	$60,800
Vessel	$37,100	$151,000
Agitator	$2,400	$3,300
Heat exchanger (SS)	$48,700	$223,100
Heat exchanger (CS)	$106,600	$358,300
Total installed cost		**$3,007,900**
Contingency and contractor's fee (18%)		$541,400
BL direct cost		**$3,549,300**

Appendix D

Compilation of Worked Examples

The final estimate money sums of the worked examples are compiled in table D.1 and D.2 for Lang from appendix B and Hand from appendix C type respectively. The estimates are converted to 2016 dollar values (CEPCI = 541.7) otherwise comparison is very limited.

The comparison of the case study is limiting in the sense that it is merely 1 case study, therefore it is unable to draw conclusions between individual methods on statistical evidence. Also the case study contained just 7 process units, therefore the expensive units (the furnace and column) have a rather large effect on the final result. Secondly the final estimate type differs among methods as displayed in tables. And thirdly some methods do not contain a database, then the results from another source were extracted and factors new factors were applied.
In two cases only a database was given (Seider et al.[17] and Sinnott and Towler[46]), then Guthrie's[79] factors were applied. The differences between their results is solely based on the database, with Guthrie estimating 25% lower than the other two databases.

Another case in which the effect of the database is visible if Chilton's[40] result is compared to Holland et al.'s[63]. These two methods are virtually identical except for the fact that Holland et al. introduced a factor to convert a database on F.O.B. prices to delivered prices on which the remaining factors work. Consequentially a very close resemblance in result is expected, however the difference database resulted in a large final estimate difference (43% off).

Cran[60] and Couper et al.[47] applied the exact same factors, so also in that case the differences, which are small, are due to the workings of the database.

The most noticeable other conclusions are based on the method type. Miller's[68] estimate is rather low, this is due to the fact that his factor values are a function of average equipment cost. The example project contained relatively high equipment value mix, which is not likely to resemble real type projects and therefore produced a low estimate.

Guthrie's[79] database has been applied in various BL methods providing excellent comparative material: The conclusion that Guthrie's factors are generally on the low side made in chapter 3.3.3, is shown to be correct.

The method by Bejan et al.[64] specifically applies a Lang factor for expansion projects. It appears however to be one of the lowest estimates, even significantly lower than the BL estimates.

Conclusion made on general trends, averages and overall scatter across the data are being made in chapter 4.1.

Table D.1: The final estimates of the example case study found in appendix B employing Lang type methods. Whenever a method did not contain a database, it was adopted from another author.

Applied method	Database	Original estimate	Scaled to 2016 $ value
		TDC	**TDC**
Lang (1947)	Chilton (1949)	$ 0.54 M	$ 3.7 M
Chilton (1949)	Chilton (1949)	$ 0.38 M	$ 2.6 M
Aries & Newton (1955)	Aries & Newton (1955)	$ 0.55 M	$ 3.4 M
Holland et al. (1974)	Guthrie (1974)	$ 1.05 M	$ 4.5 M
Peters & Timmerhaus (1991)	Peters & Timmerhaus (1991)	$ 2.13 M	$ 3.2 M
Bejan et al. (1996)	Peters & Timmerhaus (1991)	$ 1.20 M	$ 1.8 M
		BL	**BL**
Hirsch & Glazier (1958)	Aries & Newton (1955)	$ 0.49 M	$ 3.1 M
Happel & Jordan (1975)	Guthrie (1974)	$ 0.74 M	$ 3.2 M
Cran (1981)	Guthrie (1974)	$ 0.78 M	$ 3.4 M
		BL-direct	**BL-direct**
Bach (1958)	Guthrie (1974)	$ 0.85 M	$ 3.7 M
Miller (1965)	Chilton (1949)	$ 0.28 M	$ 1.5 M
Loh (2002)	Loh (2002)	$ 2.54 M	$ 3.5 M

Table D.2: The final estimates of the example case study found in appendix C employing Hand type methods. Whenever a method did not contain a database, it was adopted from another author. Seider et al.[17] and Turton et al.[45] merely contain databases, Guthrie's[79] factors were applied to find the battery limit investment cost.

Applied method	Database	Original estimate	Scaled to 2016 $ value
		TDC	**TDC**
Ulrich (1984)	Guthrie (1974)	$ 0.79 M	$ 3.4 M
Brown (2000)	Garrett (1989)	$ 1.74 M	$ 2.9 M
		BL	**BL**
Hand (1958)	Hand (1958)	$ 0.62 M	$ 3.4 M
Wroth (1960)	Hand (1958)	$ 0.67 M	$ 3.6 M
Guthrie (1974)	Guthrie (1974)	$ 0.63 M	$ 2.7 M
Klumpar & Slavsky (1985)	Guthrie (1974)	$ 2.07 M	$ 3.5 M
Garrett (1989)	Garrett (1989)	$ 1.46 M	$ 2.5 M
Gerrard, Brennan & Golonka (2000)	Garrett (1989)	$ 1.89 M	$ 3.2 M
Chauval et al. (2003)	Chauval et al. (2003)	€2.88 M	$ 3.6 M
Woods (2007)	Woods (2007)	$ 7.47 M	$ 4.0 M
Turton et al. (2008)	Turton et al. (2008)	$ 3.55 M	$ 4.8 M
Seider et al. (2009)	Seider et al. (2009)	$ 3.25 M	$ 3.5 M
Sinnott & Towler (2012)	Sinnott & Towler (2012)	$ 3.25 M	$ 3.5 M
		BL-direct	**BL-direct**
Cran (1981)	Guthrie (1974)	$ 0.46 M	$ 2.0 M
Couper et al. (2012)	Couper et al. (2012)	$ 2.10 M	$ 2.2 M

Appendix E

Elaboration on Hackney and Bauman

This appendix elaborates a bit more on the thorough methods by Hackney and Bauman. This section is referred to from chapter

J.W. Hackney

In 1960 Hackney[62] introduced his method in a comprehensive article which is actually more applicable to detailed cost estimating. In the article materials and labour are uncoupled, highlighting especially labour costs extensively. The reason it is considered (in part) a factorial method is the way how materials costs are determined. The costs for various materials other than process equipment pieces are given in most probable ranges based on his database. Hackney does a valuable suggestion: When working in an environment of many construction projects, one should database the ratio's between materials and process equipment. These ratio should be averaged and may be used to estimate future projects.

The detailed method for estimating labour however does make it none comprehensible as a factorial estimating technique: The amount of time spend on preparing manhours and labour effectiveness is out of scope for the targeted accuracy as explained in chapter 2.1.1. Therefore the method is not further elaborated on in this work, the data of Hackney however has been a valuable source for future method developers.

H.C. Bauman

The book by Bauman[18] contains a large wealth on cost estimation data; both on cost curves for equipment piece prices and detailed descriptions how to estimate auxiliary direct and indirect costs. Although the factorial method is identified as a short-cut way of estimation applying factors to find costs for piping, electrical installations, instruments, engineering etc., it is not elaborated upon. The least detailed version described in the book still requires cumbersome details not present at the beginning phase of a project such as insulation materials, amount of piling or tons of pipe. Therefore this source may merely be employed to increase the accuracy of other factorial methods by incorporating estimates on certain area's of which the engineering details are available. The data of Bauman's publication (published in 1964) has been incorporated by successive authors in their databases and novel methods.

Appendix F

Bach's Factors

The average factors extracted from Bach's[67] raw data for different battery limits and cost items are shown in figure F.1. This section is referred to from chapter 3.2.3.

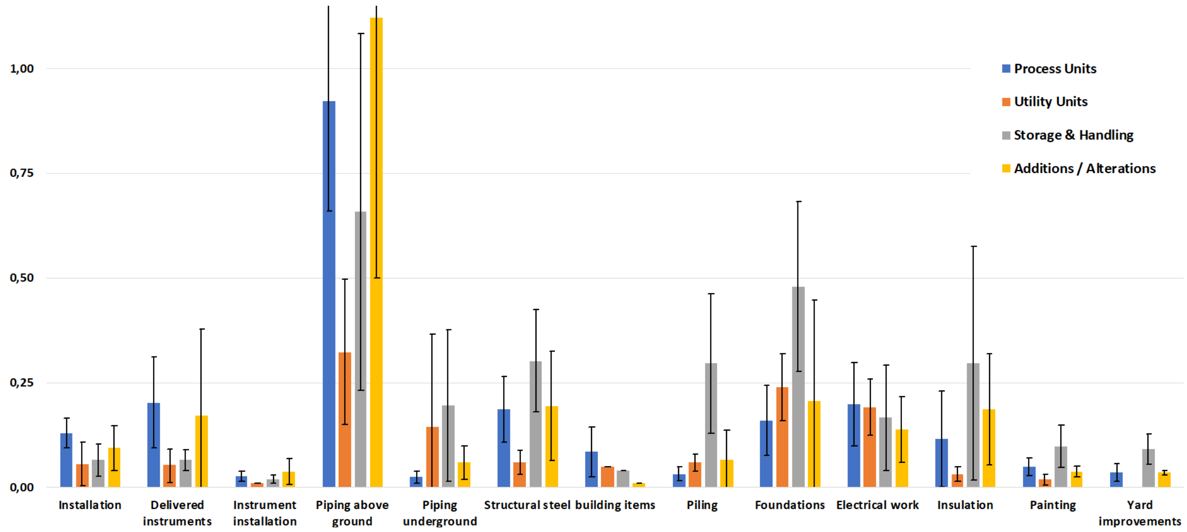

Figure F.1: Average factors plus standard deviations computed from 8 process units, 8 utility units, 6 storage handling units and 5 addition or alterations projects published by Bach[67].

Appendix G

Happel and Jordan's Factors

Factor values published by Happel and Jordan[69]. This section is referred to from chapter 3.2.3.

Table G.1: Values of material and labour components in Happel and Jordan's method[69].

Item	**Material *M***	**Labour *L***
Insulation	0.05 - 0.1	1.5
Piping	0.4 - 0.5	1
Foundations	0.03 - 0.05	1.5
Buildings	0.04	0.7
Support Structures	0.04	0.2
Fireproofing	0.005 - 0.01	5 - 8
Electrical	0.03 - 0.06	1.5
Paint and clean-up	0.005 - 0.01	5 - 8

Appendix H

Geographical Location Within Plants

The various geographical locations within a plant are defined by Miller[68]. The definitions below are directly copied from the article: "New Cost Factors Give Quick, Accurate Estimates" published in *Chemical Engineering* in 1965.

- **Battery Limits (BL)**
  This area represents all process operations. It can be defined as the boundaries enclosing a plant or process unit so as to include those facilities directly involved in the conversion of raw material to finished product. It applies to all buildings, equipment, piping, instruments, etc., that specifically involve the process or manufacturing operation. It includes that portion of the compressed air, electrical, refrigeration, steam, water, plumbing, fire protection, process-waste disposal, and air-conditioning systems, etc., that are inside the process area, but does not include the outside lines, etc., that convey such utilities or services to or from the battery-limit buildings.

- **Storage and Handling (S&H)**
  Consists of ah warehouses, storage tanks, loading, unloading, and handling facilities, etc., required for raw materials and finished products associated directly with the product being made. It includes the necessary pipelines from the point of storage to the walls or boundaries of the battery limit. It does not include storage and handling of raw materials for utilities, such as coal, fuel oil, etc., which are included with the cost of the utility. Similarly it does not include' in-process storage, which is normally charged to the battery limit, unless it is a large intermediate storage station.

- **Utilities (U)**
  Utilities refer, in general, to the production of energy and its transportation to and from the battery limit as well as to other buildings on the site. It consists of: Compressed-air plant if located outside the battery limit and outside air lines; electric power supply consisting of substation, outside lines, and yard and fence lighting; refrigeration system if located outside the battery limit consisting of refrigeration machines, and outside refrigerant lines; steam plant and outside steam lines; water supply, pumphouses, main cooling tower, and outside water lines; drains and sewers including normal sewerage treatment systems (process wastetreatment systems are part of battery limit up to a point where the discharge is safe to enter a main effluent sewer); storage and handling facilities for raw materials used in the production of utilities.

- **Services (S)**
  Represents all the remaining items of investment that are necessary to round out the plant into a fully operating unit. It includes items such as offices, laboratories, shops and lunchrooms, change houses, gatehouses, roads, ditches, railways, fences, communication system, service equipment, track scales, etc.

The last three areas are often referred to as chemical plant auxiliaries or off-site facilities.

Appendix I

Elaboration on Montfoord and Meijer

This appendix elaborates on the method by Montfoord and Meijer. This section is referred to from chapter 3.2.3.

A.G. Montfoort & F.A. Meijer

The following method is rooted in the parametric techniques, specifically Taylor's[31]. Montfoort and Meijer[70] have reformed those equations to find equation I.1. The battery limit Lang factor F_{BL} is a function of the average equipment cost $\bar{E}$ and F_{BL0}, a company specific constant. This constant may vary between companies and is calibrated from previous construction projects within the organisation.

$$F_{\mathrm{BL}} = F_{\mathrm{BL0}} \cdot \bar{E}^{0.22} \tag{I.1}$$

The exact determination of this constant is quite complex and out of scope for this project. It is explained in the publications by Taylor[31] and Montfoort and Meijer[70][93].

Reviewing Montfoort & Meijer's Method

Irrelevant of the exact working of the method, the idea of calibrating the Lang factor to company specific needs is valid. Calibration of cost estimation techniques, not necessarily the Lang factor, is already good practise in middle to large firms.

The scaling of the Lang factor with average equipment cost to a power lower than 1 is sensible for installing the auxiliaries does often not scale linearly with equipment cost. The number 0.22 results the theoretical work of Taylor and is sensibly correlated to physical data.

Appendix J

Factors from ICARUS Process Evaluator

The values for the work and labour components of factors extracted from the ICARUS Process Evaluator. These values (table J.1) were published by Loh et al.[72], his method is explained in chapter 3.2.4.

Table J.1: The values of bulk materials as given by Loh et al.[72], divided between a material and labour fraction.

		Solid		**Solid-Gas**				**Liquid**		**Gas**			
T [°C]		<200	>200	<200	<200	>200	>200	-	-	<200	<200	>200	>200
P [bar]		-	-	<10	>10	<10	>10	<10	>10	<10	>10	<10	>10
Foundations	**M**	0.04	0.05	0.05	0.06	0.06	0.06	0.05	0.06	0.05	0.06	0.06	0.05
	L	1.33	1.33	1.33	1.33	1.33	1.33	1.33	1.33	1.33	1.33	1.33	1.33
Structural Steel	**M**	0.04	0.02	0.04	0.04	0.05	0.06	0.04	0.05	0.05	0.05	0.05	0.06
	L	0.50	1.00	1.00	1.00	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Buildings	**M**	0.02	0.02	0.02	0.02	0.05	0.04	0.03	0.03	0.03	0.03	0.03	0.04
	L	1.00	1.00	1.00	0.50	0.50	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Insulation	**M**	-	0.015	0.01	0.01	0.02	0.02	0.01	0.03	0.01	0.01	0.02	0.03
	L	-	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
Instruments	**M**	0.06	0.06	0.02	0.07	0.07	0.08	0.06	0.07	0.06	0.07	0.07	0.07
	L	0.10	0.40	0.40	0.40	0.40	0.75	0.40	0.40	0.40	0.40	0.75	0.40
Electrical	**M**	0.09	0.09	0.06	0.08	0.07	0.08	0.08	0.09	0.08	0.09	0.06	0.09
	L	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.40	0.75
Piping	**M**	0.05	0.05	0.35	0.40	0.40	0.40	0.30	0.35	0.45	0.40	0.40	0.40
	L	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Painting	**M**	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	L	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
Miscellaneous	**M**	0.03	0.04	0.035	0.04	0.04	0.045	0.04	0.05	0.03	0.04	0.04	0.05
	L	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80

Appendix K

Hand's Factors

The extended version of Hand's factors tabulated on page 36.

Table K.1: The installation factors published by Hand[73] in 1958 vary among equipment types.

	Columns	Heat Exchangers	Pressure Vessels	Pumps	Compressors	Furnaces	Instruments	Miscellaneous
Field materials								
Foundations & Paving	0.10	0.05	0.05	0.05	0.05	0.10	0.05	0.05
Platforms & supports	0.15	0.25	0.20	...	...	...	0.20	0.10
Buildings	...	...	...	0.10	0.15	...	0.15	0.10
Piping	0.60	0.50	0.65	0.30	0.15	0.10	0.50	0.15
Insulation & fireproofing	0.25	0.14	0.12	0.07	0.07	0.07	0.07	0.07
Electrical	0.05	0.03	0.05	0.75	0.15	0.05	0.40	0.10
Paint, clean, test and Miscl.	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Sub-total: Field materials	**2.18**	**2.00**	**2.10**	**2.30**	**1.60**	**1.35**	**2.40**	**1.60**
Field labour								
Handle & set equipment	0.10	0.03	0.10	0.10	0.10	...	0.10	0.10
Other Construction	0.72	0.62	0.80	0.60	0.20	0.15	0.50	0.20
Sub-total: Field labour	**0.82**	**0.65**	**0.80**	**0.70**	**0.20**	**0.15**	**0.60**	**0.30**
Total: Direct cost	**3.00**	**2.65**	**3.00**	**3.00**	**1.90**	**1.50**	**3.00**	**2.50**
Indirect cost (1/3 of direct)	1.00	0.85	1.00	1.00	0.60	0.50	1.00	0.60
Installation factor *F*	**4**	**3.5**	**4**	**4**	**2.5**	**2**	**4**	**2.5**

Appendix L

Wroth's Factors

The factors published by Wroth are shown in table L.1, referred to from page 37.

Table L.1: Equipment specific installation factors published by Wroth[74], between brackets are the type of drives necessary to operate indicated.

Equipment	**Factor *F***	**Equipment**	**Factor *F***
Blender	2.0	Electric motor	8.5
Blower or fan[a]	2.5	Centrifugal pump (motor)	7.0
Centrifuge	2.0	Centrifugal pump (turbine)[a]	6.5
Centrifugal compressor (motor)	2.0	Positive displacement pump	5.0
Centrifugal compressor (turbine)[a]	2.0	Reactor	x
Reciprocating compressor (steam/gas)	2.3	Refrigeration	2.5
Reciprocating compressor (motor)	2.3	Process tank	4.1
Ejector	2.5	Storage tank	3.5
Furnace	2.0	Field erected tank	2.0
Instrument	4.1	Tower columns	4.0

[a] Includes drive: Motor or turbine. Otherwise it is excluded.

[x] No specific factor is determined, use factor that is closest related to the design.

Appendix M

Cran's Factors

The factors published by Cran are shown in table ??, referred to from page 38.

Table M.1: Cran's[60] direct cost factors associated with equipment types. Materials of construction are abbreviated: Carbon steel (CS), stainless steel (SS), aluminium (Al), copper (Co), monel (Mo), nickel (Ni), titanium (Ti), glass (Gl), graphite (Gr) and hastelloy (Ha)

Equipment	**Factor *F***	**Equipment**	**Factor *F***	**Equipment**	**Factor *F***
Agitator (CS)	1.3	Evaporator - thin film (SS)	1.9	Pump - centrifugal (Ha trim)	1.4
Agitator (SS)	1.2	Extruder	1.5	Pump - centrifugal (Ni trim)	1.7
Air heater	1.5	Fan	1.4	Pump - centrifugal (Mo trim)	1.7
Beater	1.4	Filter	1.4	Pump - centrifugal (Ti trim)	1.4
Blender	1.3	Furnace	1.3	Pump - other (SS)	1.4
Beater	1.4	Gas holder	1.3	Pump - other (CS)	1.6
Blower	1.4	Granulator for plastic	1.5	Reactor kettle (CS)	1.9
Boiler	1.5	Heat exchanger - air cooled (CS)	2.5	Reactor - kettle (Gl lined)	2.1
Centrifuge (CS)	1.3	Heat exchanger - coil in shell (SS)	1.7	Reactor - tubular (SS)	1.6
Centrifuge (SS)	1.2	Heat exchanger (Gl)	2.2	Reactor - tubular (Co)	1.8
Chimney or stack	1.2	Heat exchanger (Gr)	2.0	Reactor - tubular (CS)	2.2
Compressor - motor driven	1.3	Heat exchanger - P&F (SS)	1.5	Refrigeration plant	1.5
Compressor - steam or gas driven	1.5	Heat exchanger - P&F (CS)	1.7	Steam drum	2.0
Conveyor or elevator	1.4	Heat exchanger - S&T (SS-SS)	1.9	Tank - process (SS)	1.8
Cooling tower	1.2	Heat exchanger - S&T (CS-SS)	2.1	Tank - process (Co)	1.9
Crusher, classifier or mill	1.3	Heat exchanger - S&T (CS-Al)	2.2	Tank - process (Al)	2.0
Crystalliser	1.9	Heat exchanger - S&T (CS-Co)	2.0	Tank - storage (SS)	1.5
Cyclone	1.4	Heat exchanger - S&T (CS-Mo)	1.8	Tank - storage (Al)	1.7
Distillation column (CS)	3.0	Heat exchanger - S&T (Mo-Mo)	1.6	Tank - storage (CS)	2.3
Distillation column (SS)	2.1	Heat exchanger - S&T (CS-Ha)	1.4	Tank - field erected (SS)	1.2
Dryer - Spray or air	1.6	Instruments	2.5	Tank - field erected (CS)	1.4
Dryer - other	1.4	Miscellaneous (CS)	2.0	Turbine	1.5
Ejector	1.7	Miscellaneous (SS)	1.5	Vessel - pressure (SS)	1.7
Evaporator - calandria	1.5	Pump - centrifugal (CS)	2.8	Vessel - pressure (CS)	2.8
Evaporator - thin film (CS)	2.5	Pump - centrifugal (SS)	2.0		

- Heat exchanger designs are plate and frame (P&F) or shell and tube (S&T).

Appendix N

Brown's Factors

Values of the other factors are tabulated in tables N.1 and N.2. The instrumentation factor F_I is based on the work of Garrett[81]. The instrumentation factor is necessary to apply since Hand's or Garret's factors do not include instrumentation costs. Anyway when older values are concerned, the instrument values are generally too low for modern estimates due to increased control and safety regulations. The buildings factor F_B based on the work of Peters and Timmerhaus[14], the division into solids, mixed and fluid processes is also present in their work.

Table N.1: Values of Brown's[77] building factors F_B, based on Peter and Timmerhaus'[14] work.

Type of plant	**New plant / new site**	**New unit at existing site**	**Expansion at existing site**
Solids	1.68	1.25	1.15
Mixed	1.47	1.29	1.07
Fluids	1.45	1.11	1.06

Table N.2: Values of Brown's[77] instrument factors F_I, based on Garrett's[81] work.

Local controls	1.15
Typical chemical processing plant	1.35
Extensive centralised, computerisation control	1.55

Appendix O

Elaboration on Guthrie's Method

This appendix is an elaboration on the part of Guthrie, to be read in chapter 3.3.3. It is recommended to read that part first.

The assessment of building cost C_B is quite a tedious task. Information necessary is a plot plan including all basic characteristics of buildings: the floor space, amount of stories, foundation, roof structure. On top of that additional costs are included for air conditioning, lighting, fire prevention, etc. And equipment for laboratory, offices, shops etc. also need to be assessed. Based on the material values labour values are evaluated and summed to also find the M&L level for buildings.

The off-site costs C_O are estimated very similar to process costs (equation 3.44) with charts relating the capacities for utilities and storage to base costs, adjusting factors and installation factors provide the M&L level. Outside battery limit distribution systems and pipes also are included in off-site cost. Estimation of these parts is done based on plot plans for piping, this again shows that the required amount of engineered detail is already high.

Yard improvements estimates C_Y are also based on plot plans for fences, parking lots and other items listed on the previous page. For example fences are estimated on the meters fence, soil test per test and pumping systems per day rent.

Indirect costs may be estimated in two ways. One of them is by an overall factor as indicated by equation 3.43. A second procedure makes use of specific indirect cost factors that are given by Guthrie all equipment types in the chemical process module and off-sites module. These cost factors may also be compiled if necessary or just taken the average value given, similar to material and labour cost factors. The indirect costs for buildings and site development are then estimated via the general method. If the second method is applied the equations look like O.1 and O.2, note that the inclusion of indirect costs provides total module (TM) costs. The off-site costs are split into an off-site piping C_{OP} and off-site utilities C_{OU} cost items.

$$C_{\text{TDC}} = C_{\text{CP-TM}} + C_{\text{OU-TM}} + (C_{\text{OP}} + C_{\text{B}} + C_{\text{Y}}) \cdot F_{\text{indirect}} \tag{O.1}$$

$$C_{\text{CP-TM}} = \sum_{k=1}^{n} (F_{\text{indirect,k}} \cdot (F_{\text{M,k}} + F_{\text{L,k}}) + f_{\text{D,k}} + f_{\text{P,k}} + f_{\text{MOC,k}} + ...) \cdot E_{\text{k}} \tag{O.2}$$

The indirect costs are compiled from construction overhead, engineering and home office expenses and freight, taxes, duties and insurance. Additionally a contractor's fee and contingencies are added. A whole section of this work could be dedicated how to do this most detailed in Guthrie's method, however it was chosen to only provide ballpark figures here extracted from Guthrie, these are presented in table O.1. Based on relationships of engineering manhours per equipment type, construction overhead per field labour manhours, labour over material ratio's and total project dollar values, the factors for indirect may be determined. The amount of work to be spent to perform an estimate is large compared to other methods.

$$F_{\text{TM}} = (F_{\text{M,k}} + F_{\text{L,k}}) \cdot F_{\text{indirect}} \tag{O.3}$$

Table O.1: Approximate factors for indirect cost extracted from the work of Guthrie[79], small numbers of indirect costs are for large projects. He provides more detailed estimates in his work.

Cost item	% of	....
Total indirect costs		
Solids handling process	12 - 35	direct costs
Fluid handling process	28 - 65	direct costs
Other costs		
Contingencies	5 - 30	total module cost
Contractor fee's	3 - 3.5	total module cost
Average other cost total value	18	total module cost

Table O.2: The total module factors, extracted from Guthrie[78][79]. Total module factors are the sum of material and labour factors multiplied by a indirect cost factor excluding contingencies and contractor fee's.

Equipment	**Factor F_{TM}**	**Equipment**	**Factor F_{TM}**
Process equipment		**Other equipment****	
Air cooler	2.17	Agitator	2.47
Compression unit	2.15	Air compressor	2.44
Fired heater	2.19	Air dryer	2.86
Fired heater - field erected	1.86	Bagging machine	1.93
Furnace	2.14	Blender	2.45
Heat exchanger - double pipe	2.80	Blower or fan	2.39
Heat exchanger - shell and tube	3.17	Boiler	2.27
Hopper	1.97	Centrifuge - basket*	2.32
Pump[a] - average	3.30	Centrifuge - bowl*	2.44
Pump - centrifugal	2.75	Conveyor - bucket	3.18
Pump - reciprocating	3.83	Conveyor - other*	2.52
Pump - turbine	2.80	Crusher*	2.32
Pump[a] - vertical (axial flow)	3.05	Crystalliser - batch	2.42
Pump[a] - vertical (mixed flow)	2.70	Crystalliser - continuous	2.90
Vessel - horizontal	3.05	Dryer*	2.84
Vessel - vertical	4.16	Dust collector	2.68
		Ejector*	2.68
Off-site units		Evaporator - jacketed vessel	2.86
Boiler plant*	1.81	Evaporator* - other	3.08
Cooling tower	1.70	Filter - rotary	2.44
Power generating plant	1.46	Filter - static	3.05
Pressure storage - horizontal	2.08	Flaker	2.39
Pressure storage - spherical	1.96	Hydraulic press	2.84
Refrigeration plant	1.53	Mill	2.73
Storage tank - $<$ 40,000 gallons	1.63	Screen	1.87
Storage tank - $>$ 40,000 gallons	1.94	Stack	1.73
		Tank heater*	1.80
		Weigh scale	1.40

[a] Includes drive: Motor or turbine. Otherwise it is excluded. [*] An average value over closely related equipment items. [**] Indirect costs were assumed to be 20% of total direct costs, similar values are recommended for off-site units, for engineering work is low.

The total module factors may be extracted from Guthrie's[79] work, these are tabulated in table O.2. Most of the process equipment and off-site equipment is subdivided into the material components and labour, which is excluded here. The total module factor is the most useful factor for it includes all direct and indirect cost items, see equation O.3.

The total module factors presented in table O.2 are computed from data of Guthrie. These were not tabulated in the publication and are computed from various factors that are tabulated, excluding contractor fee's and contingencies which may be taken together as 18% extra on bare module costs, which is a reasonable value indicated by Guthrie. A risk assessment study by Guthrie revealed that at 0% contingencies a chance of a cost overrun is 75%. At 10% the chances are only 25% and are hardly lowered by increasing contingencies further for they are mainly caused by chances of scope.

At first glance it is clear that the process unit category contains higher factors than off-sites or the other equipment category, which mainly contains solid handling equipment. Both labour and materials, especially piping, are higher for process units.

Appendix P

Garrett's Factors

The tables associated with Garrett's method, described in chapter 3.3.3 on page 45.

Table P.1: Garrett's[81] 58 module factors, converting F.O.B. equipment cost to installed cost including direct and indirect cost for battery limit estimates.

Equipment	Factor *F*	Equipment	Factor *F*	Equipment	Factor *F*
Agitator	2.0	Drive - electric for other	2.0	Ion-exchange system	2.0
Agitated tank	2.5	Drive - gasoline	2.0	Mill - ball, jet, pebble rod	2.3
Blender - Ribbon	2.0	Drive - Turbine	3.5	Mill - hammer	2.8
Blender - Sigma	2.8	Dryer - fluid bed or spray	2.7	Mill - gyratory, jaw, roll	2.1
Blender - double arm / cone, twin shell	2.2.	Dryer - rotary	2.3	Press	2.4
Blower - rotary	2.2	Dust collector - bag filter	2.2	Pump - centrifugal	5.0
Blower - centrifugal	2.5	Dust collector - cyclone	3.0	Pump - chemical injection	2.8
Boiler - package or waste heat	1.8	Dust collector - Electrostatic	2.3	Pump - reciprocating	3.3
Boiler - field erected	1.9	Dust collector - venturi scrubber	2.5	Pump - turbine	1.8
Centrifuge	2.0	Evaporator - falling film	2.3	Pressure vessel - horizontal, spherical	3.1
Classifier - rake or spiral	2.3	Evaporator - forced circulation	2.9	Pressure vessel - vertical	4.2
Column - horizontal	3.1	Fan	2.2	Reactor (SS) - jacketed, no agitation	1.8
Column - vertical	4.2	Filter - belt, rotary, drum table, pan	2.4	Refrigeration system	1.5
Compressor	2.6	Filter - other	2.8	Screens	2.8
Conveyor - screw, pneumatic or roll	2.2	Furnace	2.1	Size enlargement - press, granulator, etc.	2.1
Conveyor - Belt, bucket or vibrating	2.4	Generator	2.5	Tank - atmospheric conical top	3.5
Cooler	2.7	Heat exchanger - air cooled	2.2	Tank - atmospheric field erected	2.0
Cooling tower	1.7	Heat exchanger - double pipe	1.8	Thickener / clarifier	3.0
Crystalliser	2.6	Heat exchanger - shell and tube	3.2	Vacuum equipment	3.0
Drive - electric for compr., fans, pumps	1.5	Incinerator	2.2		

Table P.2: Garrett's[81] instrument philosophy correction factor applied over the instrument money sum.

Characteristic	Philosophy correction factors
Localised control	-0.20
Pneumatic instrumentation	0.00
Centralised control	0.00
Sample analysis performed in laboratory	0.00
General-purpose process area	0.00
Explosion-purpose area	+0.10
Graphic panel display	+0.10
Special alloys required for pipeline items	+0.15
Sample analysis by only analysers	+0.20
Electronic instrumentation	+0.20
Limited-scope optimiser computer included	+0.25
All loops on computer control	+0.45

Appendix Q

Elaboration on Klumpar and Slavsky

This appendix elaborates on the method by Klumpar and Slavsky. This section is referred to from chapter 3.3.4.

I.V. Klumpar & S.T. Slavsky

Klumpar and Slavsky's method was made known in a series of three articles [82][83][84] in 1985. One year later an update on factors was given by Klumpar[85], complemented by six case examples. The method is building on previous works of Hand type techniques, however it extends the labour estimate part. It does so to counter problems related to ageing of factors, which was an issue at the time because of high money inflation periods. The line of thought is that cost databases for equipment are updated regularly, however the auxiliaries and labour factors are not while especially labour inflates at a different rate leading to wrong estimates. The database is built on 94 construction projects. However six cost curves are given in one of the articles, a serious equipment cost database is not presented and should be found elsewhere.

Every secondary material component is a specific percentage of equipment item cost, on a F.O.B. basis. The list is equal to Guthrie[78][79] thus concrete, piping, steel supports, instrumentation, insulation, electrical work and paint. The value of the factored components differs significantly, for example piping material for pumps is +/- 30% in Guthrie's work and 50% by Klumpar and Slavsky. However it is the labour component that is approached differently. Where Guthrie provides simple numbers for installation labour and a total for labour for secondary components, in Klumpar and Slavsky's method the labour for each secondary component is computed seperately based on manhours per component dollar value. This is multiplied with the local current wage W_i labour productivity $\eta_{\mathrm{IL,k}}$ for that specific labour type to estimate total labour costs. This is shown in equation Q.2 and Q.3. In which k is the running parameter for each equipment piece and i the parameter for secondary material component, e.g. concrete, piping, etc.

$$C_{\mathrm{BL}} \;=\; \sum_{k=1}^{n} E_{\mathrm{k}} \;\cdot\; (1 + F_{\mathrm{SMC,k}}) + C_{\mathrm{IL,k}} + C_{\mathrm{SLC,k}} \tag{Q.1}$$

$$C_{\mathrm{IL,k}} \;=\; F_{\mathrm{IL}} \;\cdot\; \eta_{\mathrm{IL,k}} \;\cdot\; W_{\mathrm{IL}} \;\cdot\; E_{\mathrm{k}} \tag{Q.2}$$

$$C_{\mathrm{SLC,k}} \;=\; \sum_{i=1}^{n} F_{\mathrm{i,k}} \;\cdot\; \eta_{\mathrm{i}} \;\cdot W_{\mathrm{i}} \;\cdot\; E_{\mathrm{k}} \tag{Q.3}$$

The emphasis on labour is visible in the secondary material component factors F_{SMC}, which are general and include all secondary items, for example only one set of factors discriminating between piping, supports, insulation, etc. is available for pumps. The secondary labour component factor F_{SLC} is more specialised, three sets of labour components are published based on the type of pump, each giving manhours per equipment value ratio's for all secondary material work. The installation work of the equipment piece itself is captured in the installation factor F_{IL}. The amount of estimated manhours is converted to actual dollars by correcting for labour productivity (normalised to Southern California mid-1984) and local wages per craft.

The presented method is merely an estimate of battery limit investment, thus only including process units. Utilities, buildings, general facilities and site development are still to be estimated and a method is not provided, an option would be to rely on Guthrie's publications. Factor ranges for freight to site and other direct costs are tabulated as fractions. The same is true for indirect costs and temporary construction costs. The inclusion of contingencies gives the TDC.

Reviewing Klumpar & Slavsky's Method

The method presented by Klumpar and Slavsky[82][83][84][85] is in line with Guthrie's[78][79] method. However the exact workings to include other costs than battery limit costs is vague, the components of secondary materials and labour are worked out in detail. Combining Guthrie's ways of estimating off-site and indirect costs might increase accuracy. However the methods should be compared by case studies to say anything on accuracy, for the factors between the methods are significantly different in value. This is due to the database on which the factors were developed. Another explanation might also be the indifference towards alloy usage which is not discussed at all in the articles.

The increase focus on labour comes at the cost of more effort to perform the estimate. Labour wages and productivity have to be found of each profession at the actual location, these are not easy to find. If done so, it may be unnecessary to apply location factors (see chapter 3.4.2) for these account largely for wages and productivity. This probably increases accuracy if done correctly. A concern is the normalisation to 1984 dollars in Southern California, which lies to far back in time for accurate escalation. Since Klumpar and Slavsky's method has no real follow-up it is hard to find updated cost information.

Appendix R

Chauval, Fournier and Raimbault's Factors

The factors published by Chauval et al. are shown in table R.1, referred to from page 48.

Table R.1: The total module factor values given by Chauval et al.[61], converting ex-factory price to installed modules. Drives should be included in the base price of compressors and pumps.

Principal equipment	**Factor *F***	**Special equipment**	**Factor *F***	**Utilities & storage**	**Factor *F***
Pressure vessel - column	4.05	Agitator	1.85	Boiler - package	1.50
Pressure vessel - horizontal	2.98	Mill	2.00	Boiler - erected	1.60
Heat exchanger - tubes	3.22	Centrifuge	1.80	Electricity generation	1.40
Heat exchanger - air	2.41	Conveyor	1.90	Cooling tower	1.50
Pump	2.97	Crystalliser	2.00	Refrigeration	1.40
Compressor - centrifugal	2.72	Steam ejector	1.20	Storage tank - $<150m^3$	1.65
Compressor - reciprocating	2.95	Evaporator	2.25	Storage tank - $>150m^3$	2.00
Furnace - reaction	2.41	Filter	2.00	Pressure storage - horizontal	1.40
Furnace - heating	2.39	Dryer	2.00	Pressure storage - spherical	1.85
		Vibrating screen	1.50		

Appendix S

Literature on Additional Cost Items

This appendix is referred to from page 52, chapter 3.4. The table on this page contains values for additional cost items found from 1975 onwards.

Table S.1: Estimating the costs for the acquirement of land, royalties, start-up expenses and working capital (WC) after 1975. Typical numbers are given by various authors.

	Land		**Royalties**		**Start-up**		**WC**	
Author	% of	**....**	% of	**....**	% of	**....**	% of	**....**
1976: Baasel[16]					5-20	TDC		
1989: Garrett[81]	3-10	EC			5-10	TDC	10-20	TDC
1991: Peters & Timmerhaus[14]	6	EC			8-10	TPI	10-20	TPI
1993: Humphreys[10]					0-10	TCI	10-20	TPI
1996: Bejan et al.[64]	0-10	EC			5-12	TPI	10-20	TCI
2000: Gerrard[15]					1-10	TPI	10-30	TPI
2003: Couper[7]	3	TPI			6-10	TPI	15-25	TPI
2003: Sila[11]	1-2	TDC			0-10	TCI	20	TPI
2007: Brown[77]					5-15	TDC		
2007: Woods[44]	1-2	TDC			15-40	TDC	15-40	TDC
2008: Green & Perry[19]					3	BL	15-25	TCI
2008: Maroulis & Saravacos[66]							25	TDC
2009: Seider et al.[17]	2	TDC	2	TDC	2-30	TDC	15	TCI
2018: Harmsen et al.[99]							5-30	TCI

EC: Equipment cost

Appendix T

How to Account for Plant Location

This appendix provides some more information on location factors and explains the implementation of it. It is referred to from chapter 3.4.2 on page 53.

In the first publications on factorial estimation techniques the differences that could occur between locations were described in a quantitative manner, however not quantifying the issue. The mere factorial method accounting for location initiated differences within its structure was developed by Klumpar and Slavsky[82][83][84][85], see page 46. The local labour wage per craft and productivity are taken taken as an input, already largely implementing local conditions.

However other methods lack such an implementation and rely on the location correction factor. These gained popularity after Bridgwater[102] published the most extensive list for the time in 1979. It contains 33 factors (mainly for European countries) providing average construction costs for chemical plants of similar function. Location factors are easy in use, see equation T.1. The fraction between the actual locations factor value and the factorial estimate technique's base (mostly in the U.S.A.) location factor provides the costs for the construction of a similar plant at that specific location.

$$C_{\text{location A}} = C_{\text{location B}} \cdot \frac{F_{\text{location A}}}{F_{\text{location B}}} \tag{T.1}$$

Location cost factors are continuously subject to change across time. Adjusting it with the help of time cost indices is not sufficient, for changes occur at different paces across the globe. Recently Remer in collaboration with various authors[48][103][104] have regularly updated lists of where to find international cost inflation indexes for different locations. It is however takes some effort to accommodate these numbers into the actual estimate. More easy to apply are on cost factors in the style of Bridgwater by Garrett[81], Brown[76][77] derived from Perry and Green[19] and more elaborately by Richardson[105] who provides a thorough analysis for more than 40 and more than 60 locations within and outside the U.S.A. respectively. The latter resource also shows the differences in cost items per region plus local regulations.

Appendix U

Case Study Results

This appendix contains the individual results on each of the 12 case studies, generally discussed in chapter 4.3.3 on page 64. The individual results do not elaborate on the individual pieces of equipment, for the larger picture is more relevant.

Each case study presentation is built upon three figures and one graph. The first figure shows the equipment mix according to a reference value or the average of the applied techniques providing the reader with a global idea on the case type. The table summarises the final results for each factorial technique in terms of F.O.B. equipment price, installed battery limit cost and the apparent factor, which couples the former two items. If a reference value is available, also the relative position (or assumed error) of the estimate compared to the reference is shown in as a percentage. As discussed at the start of this work (chapter 2.1.1), a factorial technique is considered accurate enough that the actual value deviates between -25% and +30% of the found value. The relative position of the reference to the estimate makes it possible for the reader to quickly evaluate the accuracy.

Notably the assumed accuracy is even so dependent on the accuracy of the reference value. In some cases it is doubtful, whenever that is the case it is addressed in that particular section.

The second figure reveals the battery limit estimates constructed to a normally distributed curve, the normalised probability density function: The area under the graph equals unity. Although strictly speaking the curve should be skewed due to unbalanced influence of over and under estimation, the normal distribution is a fair assumption. It is noted that in most cases this results in a broad distribution, thus providing minor predictive value. As a rule of thumb the 68% confidence interval falls between the average plus minus the standard deviation and the 95% confidence interval between the average plus minus 2x the standard deviation. However these intervals extracted from the data appear to be relatively large.

Note that all dollar values are corrected to 2016 values, the CEPCI value for that period is 541.7.

U.1 Case 1: Fluid Catalytic Cracking (small)

Fluid catalytic cracking (FCC) is a proven technology and aimed at converting gas oil and heavier streams in a refinery to lighter products. It does so by a reaction facilitated by circulating solid catalyst particles in a fluidised bed. The case study equipment profile is shown in figure U.1, the design presented in the case description by the NREL[114] is mainly based around a complicated reactor system to produce 100,000 tonne per day. The other pieces are merely of supportive nature.

The reference values for case 1 is extracted from the report by NREL[114] and is based upon vendor quotes, which are considered to be more reliable than factorial methods. Therefore it may be safely assumed that the reference value is close to the real value.

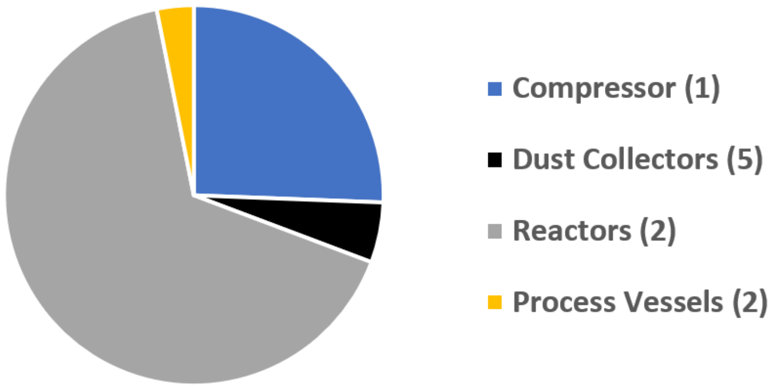

Figure U.1: Equipment mix of case 1 depicted as per dollar off the reference estimate by NREL[114].

Table U.1: The results of applying the estimation techniques for case 1.

	F.O.B. price [M$]	**Installed BL price [M$]**	**Correction Error in BL Estimate [%]**	**Apparent Factor [-]**
Woods	5.4	11.1	+8%	2.06
Turton et al.	1.1	3.3	+262%	3.00
Seider et al. - IChemE	1.8	6.2	+93%	3.44
Seider et al. - Hand	1.8	5.5	+117%	3.06
Sinnott & Towler - IChemE	4.3	11.8	+1%	2.74
Sinnott & Towler - Hand	4.3	13.0	-8%	3.02
Average value [$\bar{\$}$]	**3.2**	**8.5**	**+41%**	2.89
Standard deviation [σ]	1.8	3.6		0.42
Coefficient of Variation [$\sigma/\bar{\$}$]	0.56	0.43		0.15
Reference Value	**2.5**	**11.9**		

It is clear from table U.1 and figure U.2 that the estimates by Woods and Sinnott and Towler were successful, while the other underestimated. Though the reference value falls within the the 68% confidence interval for the expected value based upon the six estimates. The underestimates are due to the fact that the methods cannot include the extra costs made by complex internals in the reactors, for which the company quotations made in the reference can.

Analysing the individual results more closely the source of success seems to be present in the F.O.B. price and not the apparent factor, which are all quite similar. Table ?? reveals that only Woods, whose database contains a vertical riser unit, was able to correctly estimate the reactor costs, others underestimated. Because approximately 75% of the costs are made by the reactors, this was crucial in the estimation process. The estimates based upon Sinnott and Towler's database were relative close on the reactor estimate, but more importantly were compensated by an overestimate for the compressor, the latter is a repetitive occurrence in other cases. Although the final estimate is close to the reference value, it is due to a coincidence than a solid estimate procedure.

The overestimate of process vessels for Sinnott and Towler also stands out, however the effect on the final outcome is minimal. Dust collectors, which in this case were all cyclones were underestimated by every method. It is unknown whether this is a inconsistent included in every method or if the reference value is off. A possibility is the fact that the cyclones are closely interlinked with the reactor, which is a factor included in the reference value.

Figure U.2: The constructed normal distribution curve for case 1. The green line indicates the reference value.

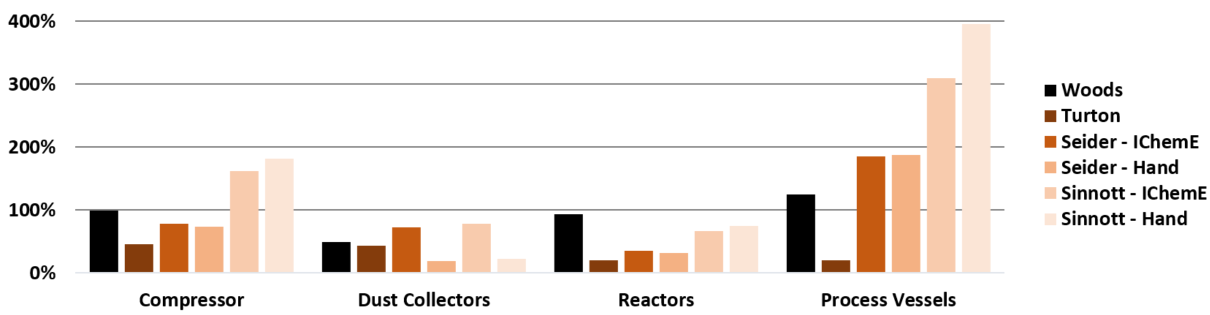

Figure U.3: The estimated value per equipment class, shown relatively to the value in the NREL[114] reference (100%).

U.2 Case 2: Fluid Catalytic Cracking (large)

Case 2 is virtually identical (a few adaptations) to case 1, except for the fact that the intended product output is 2,500,000 tonne per day.

The reference values for case 2 is extracted from the report by NREL[114] and is based upon vendor quotes, which are considered to be more reliable than factorial methods. Therefore it may be safely assumed that the reference value is close to the real value.

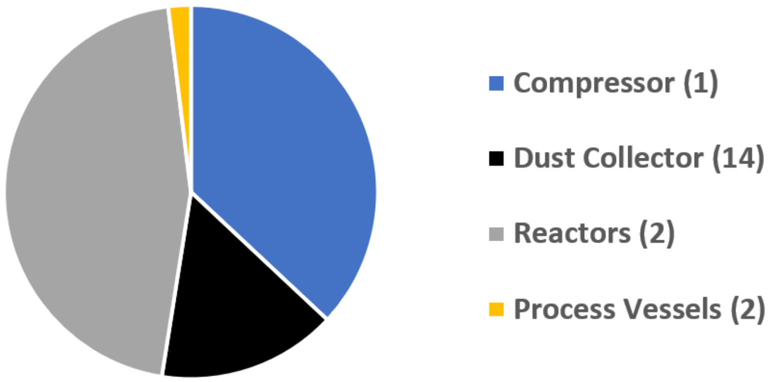

Figure U.4: Equipment mix of case 1 depicted as per dollar off the reference estimate by NREL[114].

Table U.2: The results of applying the estimation techniques for case 2.

	F.O.B. price [M$]	**Installed BL price [M$]**	**Correction Error in BL Estimate [%]**	**Apparent Factor [-]**
Woods	27.7	60.5	+84%	2.18
Turton et al.	41.6	105.6	+5%	2.54
Seider et al. - IChemE	13.3	38.8	+187%	2.92
Seider et al. - Hand	13.3	36.9	+202%	2.77
Sinnott & Towler - IChemE	24.3	66.8	+67%	2.75
Sinnott & Towler - Hand	24.3	71.0	+57%	2.92
Average value [$\bar{\$}$]	**26.7**	**63.3**	**+76%**	2.68
Standard deviation [σ]	10.1	23.0		0.26
Coefficient of Variation [$\sigma/\bar{\$}$]	0.38	0.36		0.10
Reference Value	**23.8**	**111.3**		

Similarly to case 1 the reactor estimate is the largest contributor, as shown in figure U.4. It is therefore surprising to note that Sinnott and Towler's estimates and Woods' have failed to estimate it correctly on the larger scale. Again the internal structure of the reactor has inhibited the ability to correctly estimate the reactor part as indicated in figure U.6. Turton et al. did overshoot the reactor estimate, probably because the factor for material of construction (nickel) was too high. This overcompensation allowed the method of Turton et al. too be close to the reference value, as shown in figure U.5.

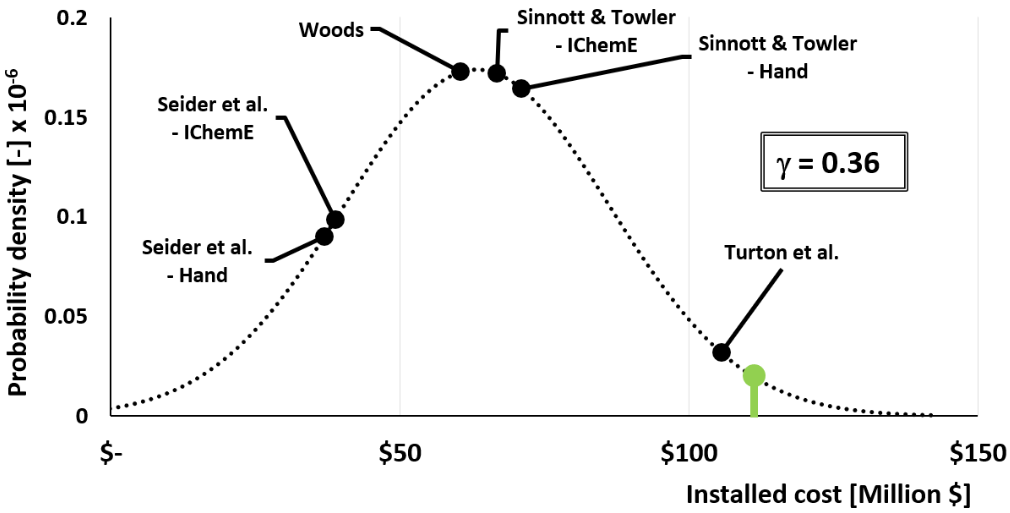

Figure U.5: The constructed normal distribution curve for case 2. The green line indicates the reference value.

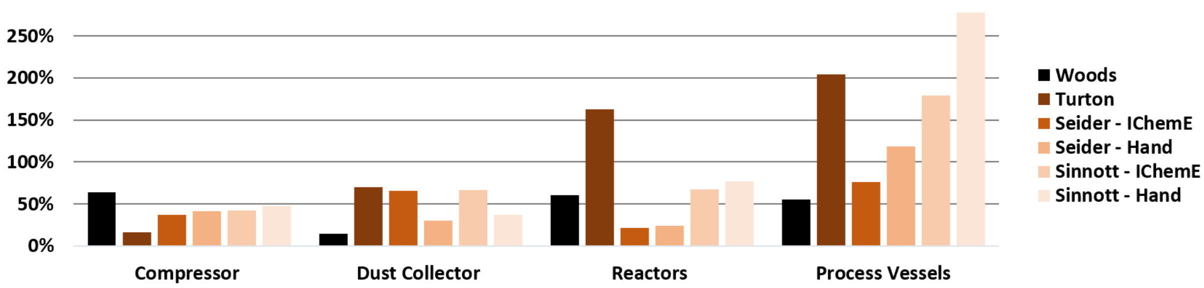

Figure U.6: The estimated value per equipment class, shown relatively to the value in the NREL[114] reference (100%).

U.3 Case 3: Steam Methane Reforming (small)

Steam methane reforming (SMR) is a process of converting natural gas together with steam to synthesis gas. Case study 3 contains a very small design of a modular unit producing 0.11 tonne hydrogen per day, reported on by the NREL[114].

The reference values for case 3 is extracted from the report by NREL[114] and is based upon vendor quotes, which are considered to be more reliable than factorial methods. Therefore it may be safely assumed that the reference value is close to the real value.

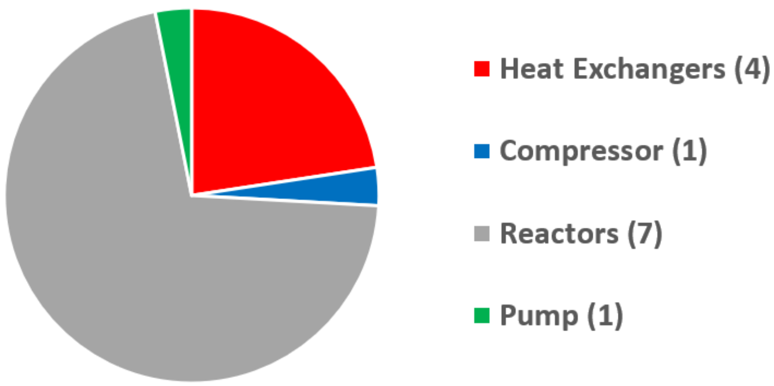

Figure U.7: Equipment mix of case 1 depicted as per dollar off the reference estimate by NREL[114].

Table U.3: The results of applying the estimation techniques for case 3.

	F.O.B. price [M$]	**Installed BL price [M$]**	**Correction Error in BL Estimate [%]**	**Apparent Factor [-]**
Woods	0.39	1.5	-82%	3.85
Turton et al.	0.15	0.5	-45%	3.33
Seider et al. - IChemE	0.31	1.4	-80%	4.52
Seider et al. - Hand	0.31	0.8	-66%	2.58
Sinnott & Towler - IChemE	0.85	2.8	-90%	3.29
Sinnott & Towler - Hand	0.85	2.6	+89%	3.06
Average value [$\bar{\$}$]	**0.43**	**1.6**	**-83%**	3.44
Standard deviation [σ]	0.26	0.9		0.61
Coefficient of Variation [$\sigma/\bar{\$}$]	0.61	0.53		0.18
Reference Value	**0.11**	**0.27**		

Table U.7 shows that reactors are the key parameter within this system, second are heat exchangers. From table U.3 and figure U.8 it is clear that no method was able to predict the correct value within the required accuracy. The scatter of data is also high, leading to a broad normal distribution. The reference value falls within the 95% confidence interval, however the predictive value of the system is very low in this manner. Actually the data predicts that with 95% confidence the values is between $0 and $3,600,000 dollars.

The reason for the poor estimation is found in the small flow rates, almost all correlations for equipment prices were employed outside of their applicable range. Especially Sinnott & Towler suffer from this, because of the nature of their database. If the size parameter approaches zero, the cost outcome is K_1, see page 49.

Figure U.8: The constructed normal distribution curve for case 3. The green line indicates the reference value.

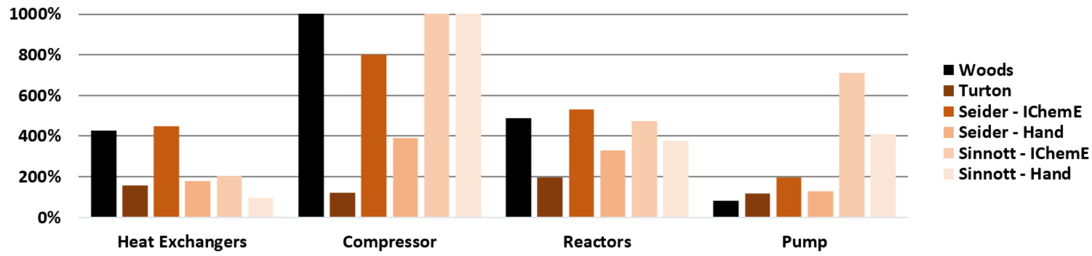

Figure U.9: The estimated value per equipment class, shown relatively to the value in the NREL[114] reference (100%).

U.4 Case 4: Steam Methane Reforming (large)

Case 2 is similar to case 3, except for the fact that hydrogen output is 2,500,000 tonne per day. The system is no longer modular, but an industrial scale. An assumption is that high pressure feed is available, therefore the compressor was excluded from the design.

The reference values for case 4 is extracted from the report by NREL[114] and is based upon vendor quotes, which are considered to be more reliable than factorial methods. Therefore it may be safely assumed that the reference value is close to the real value.

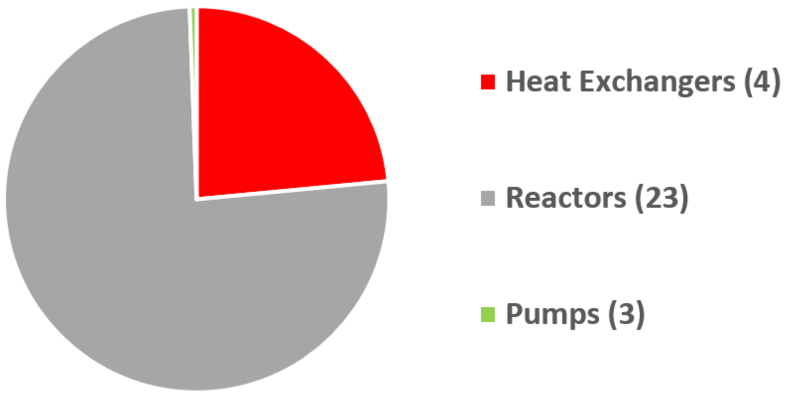

Figure U.10: Equipment mix of case 1 depicted as per dollar off the reference estimate by NREL[114].

Table U.4: The results of applying the estimation techniques for case 4.

	F.O.B. price [M$]	**Installed BL price [M$]**	**Correction Error in BL Estimate [%]**	**Apparent Factor [-]**
Woods	74.6	140.8	+88%	1.89
Turton et al.	81.2	177.9	+49%	2.19
Seider et al. - IChemE	42.2	110.4	+140%	2.62
Seider et al. - Hand	42.2	125.8	+110%	2.98
Sinnott & Towler - IChemE	57.5	154.4	+71%	2.69
Sinnott & Towler - Hand	57.5	217.3	+22%	3.78
Average value [$\bar{\$}$]	**107.1**	**264.6**	**+71%**	2.69
Standard deviation [σ]	15.2	35.2		0.60
Coefficient of Variation [$\sigma/\bar{\$}$]	0.24	0.23		0.22
Reference Value	**107.1**	**264.6**		

As shown by table U.4 and figure U.11 the estimate techniques were off. The opposite to case 3 is due to this fact, namely that many correlation were out of range again only now at the high side. The relatively high factor by Hand combined with high values of the Sinnott and Towler database pushed one estimate close to the reference value and may be considered within the accuracy requirements. Generally speaking the factorial techniques were unable to correctly predict the outcome of this case study as shown by the normalised distribution curve.

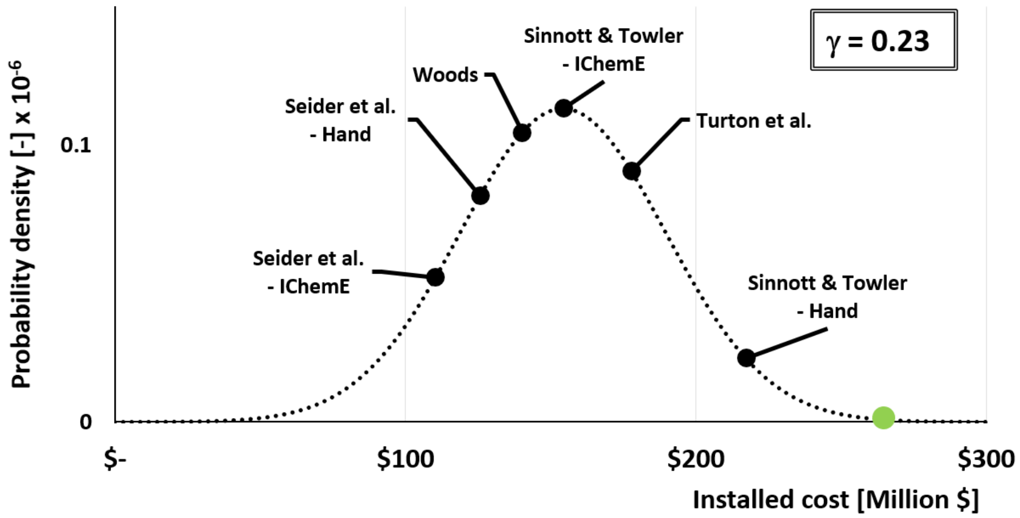

Figure U.11: The constructed normal distribution curve for case 4. The green line indicates the reference value.

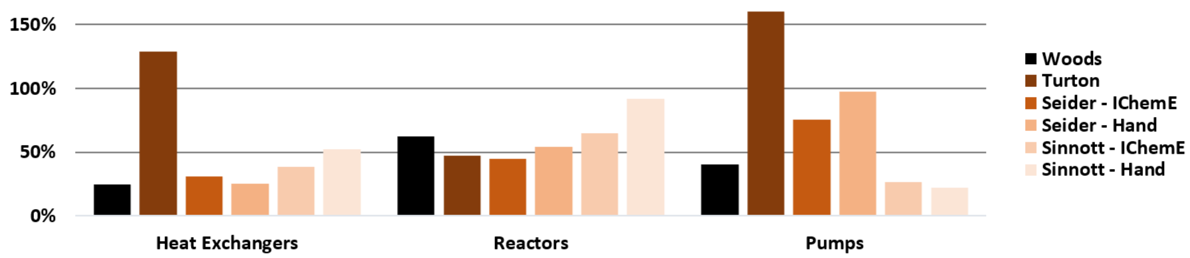

Figure U.12: The estimated value per equipment class, shown relatively to the value in the NREL[114] reference (100%).

U.5 Case 5: Natural Gas Liquid Expander (small)

The NREL[114] reported on a natural gas liquid (NGL) expander project with a capacity of 460 tonne per day. This is he basis of case 5, in which the gasses mainly contained ethane and propane. The technology applied in the case is already mature.

The reference values for case 5 is extracted from the report by NREL[114] and is based upon vendor quotes, which are considered to be more reliable than factorial methods. Therefore it may be safely assumed that the reference value is close to the real value.

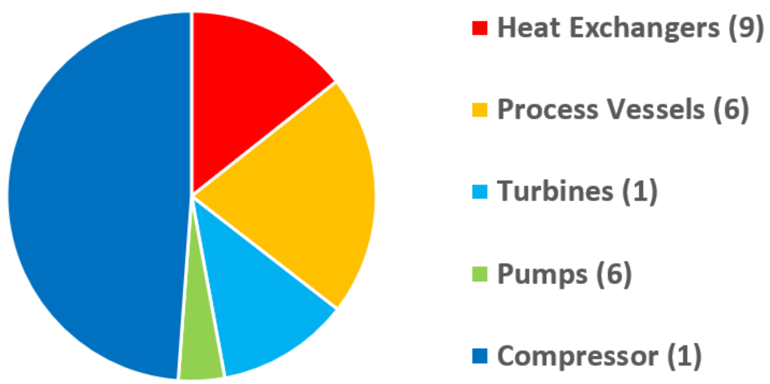

Figure U.13: Equipment mix of case 1 depicted as per dollar off the reference estimate by NREL[114].

Table U.5: The results of applying the estimation techniques for case 5.

	F.O.B. price [M$]	**Installed BL price [M$]**	**Correction Error in BL Estimate [%]**	**Apparent Factor [-]**
Woods	5.6	14.2	-8%	2.54
Turton et al.	3.8	11.1	+17%	2.92
Seider et al. - IChemE	4.7	15.0	-13%	3.19
Seider et al. - Hand	4.7	13.1	-1%	2.79
Sinnott & Towler - IChemE	6.7	20.1	-35%	3.00
Sinnott & Towler - Hand	6.7	20.9	-38%	3.12
Average value [$\bar{\$}$]	**5.2**	**15.7**	**-17%**	2.93
Standard deviation [σ]	1.1	3.6		0.22
Coefficient of Variation [$\sigma/\bar{\$}$]	0.21	0.23		0.07
Reference Value	**5.3**	**13.0**		

Figure U.13 shows that approximately half of the costs is associated with a single compressor. Other parts are contributed by a battery of heat exchangers, process vessels, pumps and a turbine. Table U.5 and figure U.14 show that the estimate was relatively successful. Although Sinnott and Towler's estimates were off, the others are very close to the reference value.

Let's take a look at figure U.15. The reasons of the overestimates by Sinnott and Towler are again partly due to the overestimation of compressor cost, which is a large contributor. Turbines (containing a compressor) are seriously overestimated.

Overall seen other deviations in estimates per equipment class are observed, however small. These variations normally occur in factorial estimation techniques, and cancel out as the amount of units or estimates increases. The size of the heat exchangers was small and thus was the price per item. Because the factors by the IChemE method are higher for low prices, the factor and thus the installed price is high compared to Hand's.

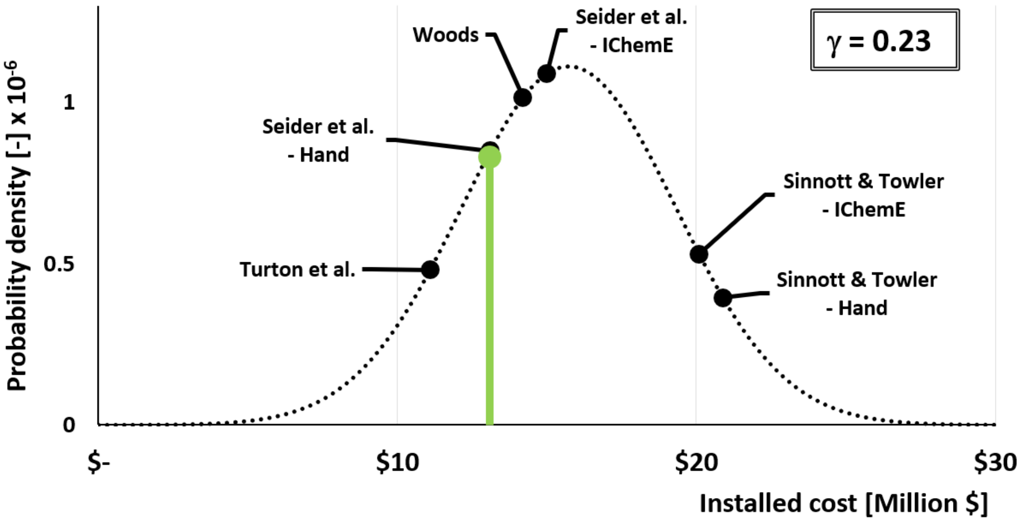

Figure U.14: The constructed normal distribution curve for case 5. The green line indicates the reference value.

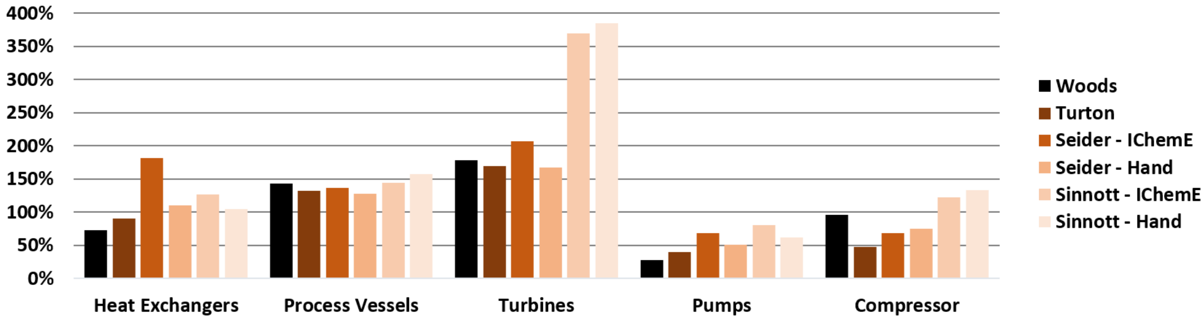

Figure U.15: The estimated value per equipment class, shown relatively to the value in the NREL[114] reference (100%).

U.6 Case 6: Natural Gas Liquid Expander (large)

The design for case 6 is similar to case 5, apart from the fact that the output is increased to 3,400 tonne per day.
The reference values for case 6 is extracted from the report by NREL[114] and is based upon vendor quotes, which are considered to be more reliable than factorial methods. Therefore it may be safely assumed that the reference value is close to the real value.

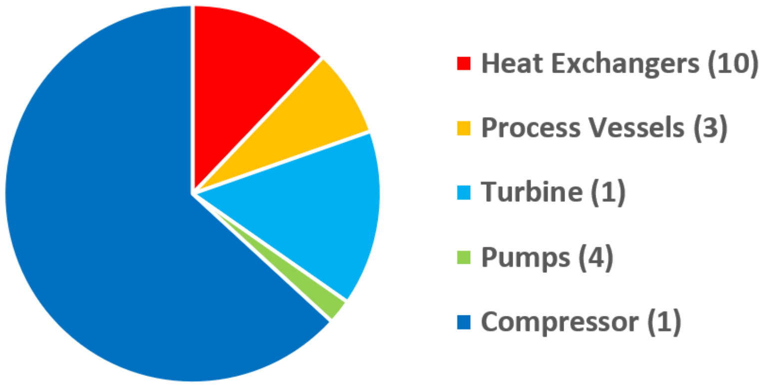

Figure U.16: Equipment mix of case 1 depicted as per dollar off the reference estimate by NREL[114].

Table U.6: The results of applying the estimation techniques for case 6.

	F.O.B. price [M$]	**Installed BL price [M$]**	**Correction Error in BL Estimate [%]**	**Apparent Factor [-]**
Woods	17.7	48.9	+3%	2.76
Turton et al.	16.8	49.5	+2%	2.95
Seider et al. - IChemE	17.8	46.7	+8%	2.62
Seider et al. - Hand	17.8	47.2	+7%	2.65
Sinnott & Towler - IChemE	19.9	53.4	-6%	2.68
Sinnott & Towler - Hand	19.9	63.0	-20%	3.17
Average value [$\bar{\$}$]	**18.1**	**51.4**	**-2%**	2.81
Standard deviation [σ]	1.1	5.6		0.19
Coefficient of Variation [$\sigma/\bar{\$}$]	0.06	0.11		0.07
Reference Value	**20.3**	**50.3**		

From figure U.16 it is clear that the singular compressor is even a larger part of the total costs. Table U.6 and figure U.17 show that all methods were successful, the Sinnott & Towler - Hand combination also falls just in the limits. The constructed probability density function is narrow and correctly predicts the reference value.

Interestingly in contrast case 5 at a lower capacity different results are obtained per equipment type, shown by comparing figure U.15 and U.18. Heat exchangers and compressors were more correctly estimated at a low capacity and process vessels, pumps and turbines were better estimated at a high capacity.

Figure U.17: The constructed normal distribution curve for case 6. The green line indicates the reference value.

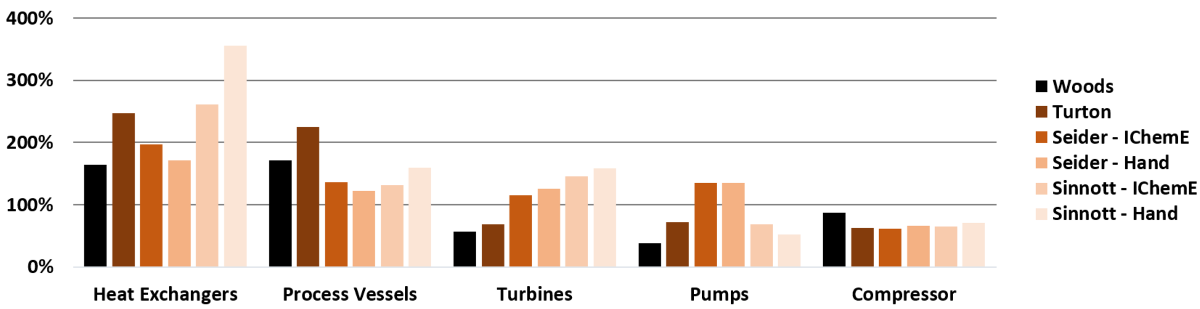

Figure U.18: The estimated value per equipment class, shown relatively to the value in the NREL[114] reference (100%).

U.7 Case 7: Ammonia Synthesis Loop

Case 7 is a part of an investigation into the ammonia economy powered by wind energy. The research is performed by Morgan[115]. The battery limit investment found corresponds to a ammonia synthesis loop, which recycles the reactants through an adiabatic reactor, producing 300 tonne ammonia per day.

The reference value found is sketch for it only costs out of two data points by from Duncan[120] on a ammonia plant construction project and Tremel et al.[121] on a techno-economical analysis. The capacities in both publications was larger than the actual case, extrapolation was necessary. On top of that the ammonia synthesis loop is merely a separate unit of a larger factory, thus the reference values might contain more process units than those listed in case study 7.

It may therefore not come as a surprise that the estimates were on the low side of the reference value, as shown in table U.7 and figure U.20. The reported errors may, because of the reasons above, not be given much weight. On the other hand, as the probability density function indicates, the coefficient of variation is high and thus the estimation techniques do not agree well on case 7. The uncertainty about the right outcome remains unknown.

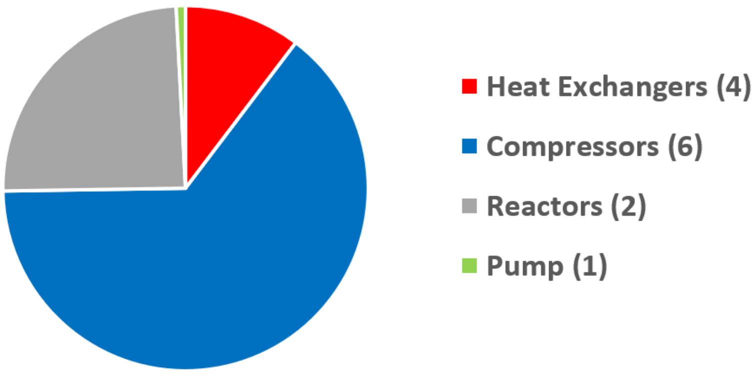

Figure U.19: Equipment mix of case 7 depicted as per dollar off the average values.

Table U.7: The results of applying the estimation techniques for case 7.

	F.O.B. price [M$]	Installed BL price [M$]	Correction Error in BL Estimate [%]	Apparent Factor [-]
Woods	22.4	40.9	+147%	1.83
Turton et al.	8.9	29.2	+247%	3.28
Seider et al. - IChemE	19.0	42.3	+139%	2.23
Seider et al. - Hand	19.0	38.6	+162%	2.03
Sinnott & Towler - IChemE	25.4	61.4	+65%	2.42
Sinnott & Towler - Hand	25.4	72.1	+40%	2.84
Average value [$\bar{\$}$]	**18.9**	**47.4**	**+113%**	2.44
Standard deviation [σ]	6.2	14.6		0.49
Coefficient of Variation [$\sigma/\bar{\$}$]	0.33	0.31		0.20
Reference Value		**101.2**		

The major contributor to the uncertainty are the six compressors of the system, indicated in figure U.19. Figure U.21 shows that the variation in compressor prices is not shockingly different. However because approximately 75% of the price is determined by the compressors, other equipment categories are unable to level off differences in compressor price.

Figure U.20: The constructed normal distribution curve for case 7. The green line indicates the reference value.

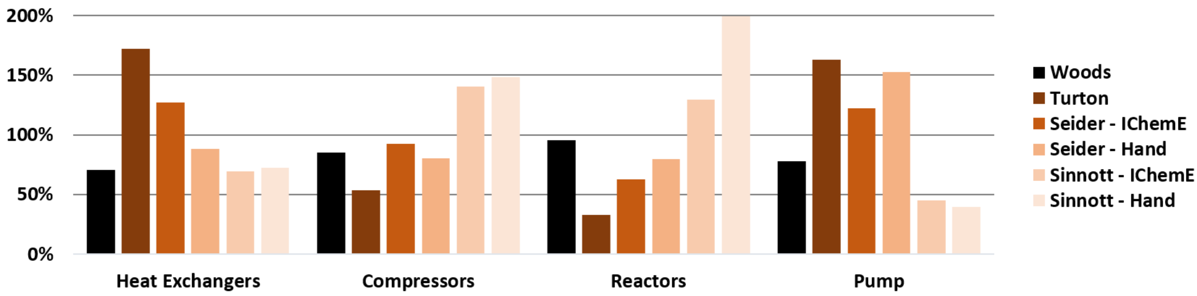

Figure U.21: The estimated value per equipment class, shown relatively to the average value (100%).

U.8 Case 8: Cryogenic Air Separation

Case 8 is part of the same wind-powered ammonia economy design by Morgan[115]. Now a second battery limit investment is tested, a air cryogenic air separation unit plant. This is a proven technology and applied many times worldwide. The projected size is 250 tonne nitrogen per day.

The reference value is extracted from industrial packages offered by AirLiquide[122] and from a part of an economic analysis by Kreutz et al.[123] on the production of hydrogen, whose design also contains an commercially available air separation unit.

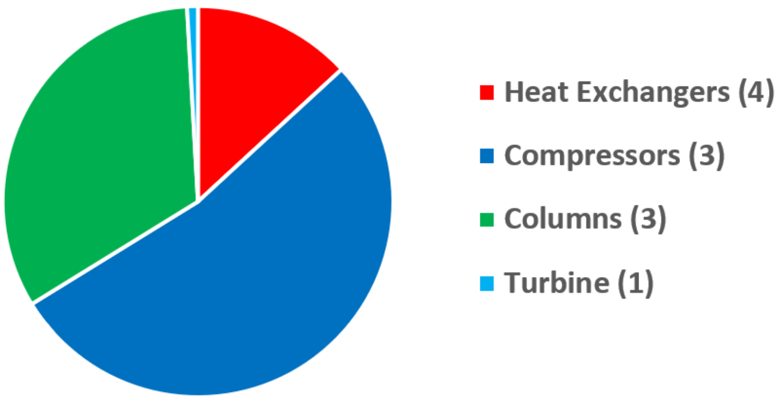

Figure U.22: Equipment mix of case 8 depicted as per dollar off the average values.

Table U.8: The results of applying the estimation techniques for case 8.

	F.O.B. price [M$]	**Installed BL price [M$]**	**Correction Error in BL Estimate [%]**	**Apparent Factor [-]**
Woods	5.5	11.6	+5%	2.11
Turton et al.	3.1	10.6	+15%	3.42
Seider et al. - IChemE	4.6	14.3	-15%	3.11
Seider et al. - Hand	4.6	11.7	+4%	2.54
Sinnott & Towler - IChemE	7.2	19.1	-36%	2.65
Sinnott & Towler - Hand	7.2	15.7	-22%	2.18
Average value [$\bar{\$}$]	**5.1**	**13.8**	**-12%**	2.67
Standard deviation [σ]	1.5	2.9		0.47
Coefficient of Variation [$\sigma/\bar{\$}$]	0.29	0.21		0.18
Reference Value		**12.2**		

Figure U.22 indicates that the equipment mix is mainly consisting out of compressors, distillation columns and heat exchangers. Table U.8 and figure U.23 show that all methods, except Sinnott & Towler - IChemE, successfully predicted the reference value within the required accuracy.

The reason of Sinnott & Towler - IChemE being off may be found by investigating figure U.24. The compressors are in a large part responsible for the F.O.B. equipment price. However Sinnott & Towler - Hand was able to come close to the reference value, which is due to a relative low factor value for compressors in Hand's method.

The high value for the stainless steel turbine by Turton may be explained by the high material of construction factor and installation factor presented in their method. The influence on the end result is negligible.

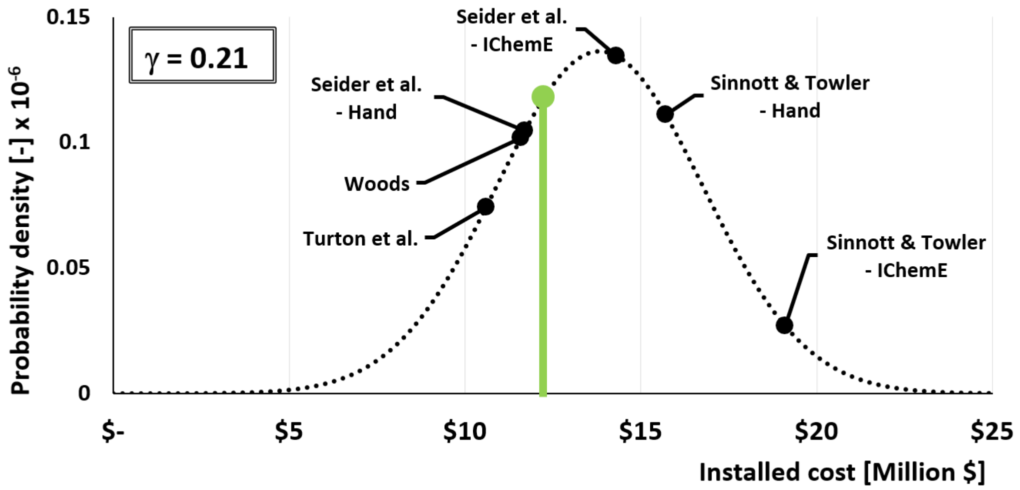

Figure U.23: The constructed normal distribution curve for case 8. The green line indicates the reference value.

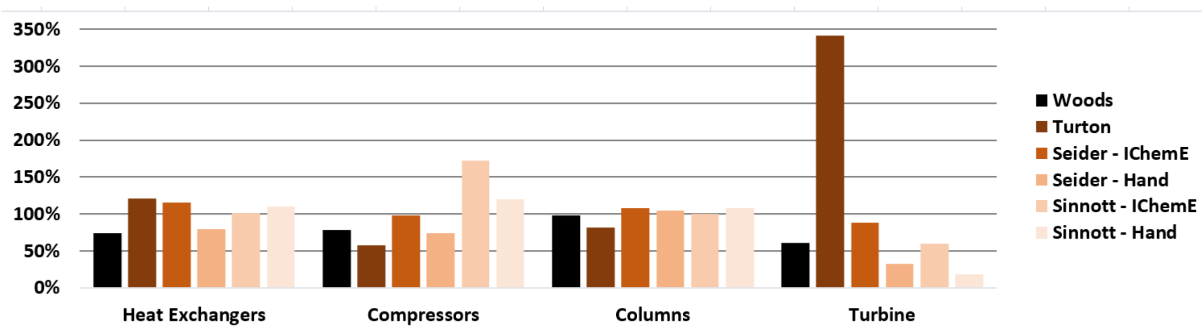

Figure U.24: The estimated value per equipment class, shown relatively to the average value (100%).

U.9 Case 9: Methanol from Syngas

Methanol production from syngas is a proven technology. The equipment list was downloaded from IPPE[116], which is a seller of second-hand process plants. The capacity of the plant is 310 tonne per day.

Reference values were easily available, nine recent (2014-2016) projects constructed in the United States and described by Turage[124] were selected as a reference.

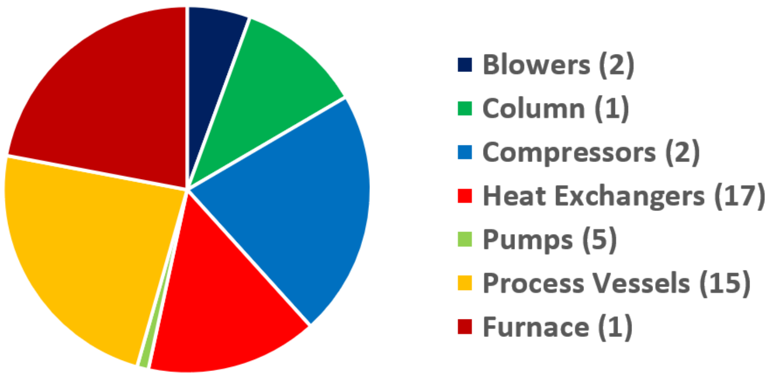

Figure U.25: Equipment mix of case 9 depicted as per dollar off the average values.

Table U.9: The results of applying the estimation techniques for case 9.

	F.O.B. price [M$]	Installed BL price [M$]	Correction Error in BL Estimate [%]	Apparent Factor [-]
Woods	9.0	26.0	+6%	2.89
Turton et al.	9.4	24.7	+11%	2.63
Seider et al. - IChemE	7.6	24.6	+12%	3.24
Seider et al. - Hand	7.6	22.8	+20%	3.00
Sinnott & Towler - IChemE	9.2	28.9	-5%	3.14
Sinnott & Towler - Hand	9.2	30.8	-11%	3.35
Average value [$\bar{\$}$]	**8.8**	**26.3**	**4%**	3.04
Standard deviation [σ]	0.7	2.7		0.24
Coefficient of Variation [$\sigma/\bar{\$}$]	0.08	0.10		0.08
Reference Value		**27.4**		

Figure U.25 shows a diversified equipment mix. Table U.9 and figure U.26 show a positive image. All methods were within the accuracy requirement and show minimal scatter around the average. On top of that the reference value is close to the average. Multiple reasons may be cause of the success: The technology is mature and thus incorporated in the databases, which are often partly constructed out of old data. A second reason could be the relative high amount of equipment items and type of equipments having an averaging effect on the end results. Thirdly it is known that many databases include a high amount of data from the petro-chemical industry to which methanol production is closely related.

A relatively low amount of scatter in any equipment class is visible in figure U.27. Only the blower type stands out. The high numbers (Woods and Sinnott & Towler) correlated volumetric flow to a F.O.B. price, while Turton et al.'s and Seider et al.'s correlation was based upon machine power. A plausible explanation could be a mistake made in setting up the equipment list with equipment characteristics. Anyway the influence is small on the final result.

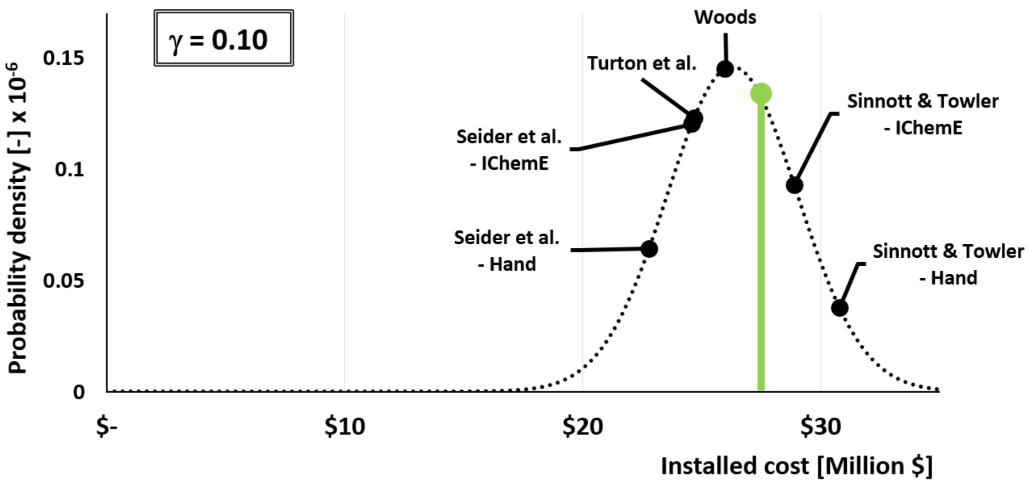

Figure U.26: The constructed normal distribution curve for case 9. The green line indicates the reference value.

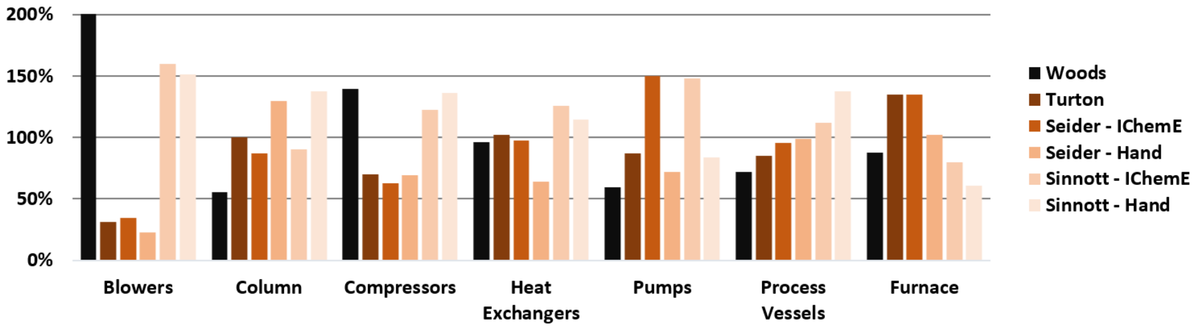

Figure U.27: The estimated value per equipment class, shown relatively to the average value (100%).

U.10 Case 10: Soybean Oil Body Extraction

The extraction of oil bodies from Soybeans was a case study performed by a group of students, van Amsterdam et al.[117], as a part of the design course at the TU Delft. The set up consist out of cell lysis, centrifugation, filtering and drying to produce 12.5 tonne of intact oil bodies per day. No reference value is available for this process, for the first economically viable plant is yet constructed.

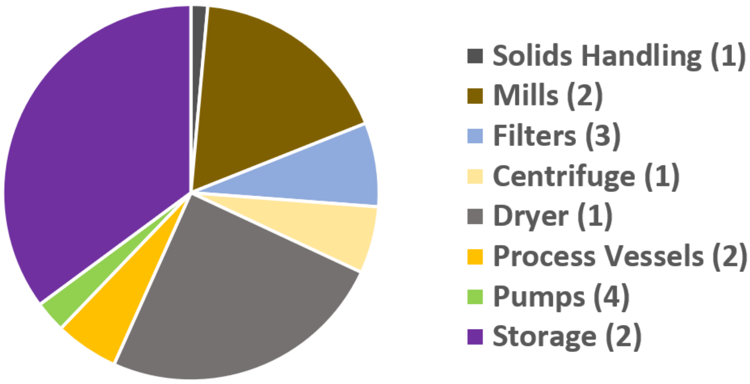

Figure U.28: Equipment mix of case 10 depicted as per dollar off the average values.

Table U.10: The results of applying the estimation techniques for case 10.

	F.O.B. price [M$]	**Installed BL price [M$]**	**Apparent Factor [-]**
Woods	3.7	10.6	2.86
Turton et al.	4.0	16.0	4.00
Seider et al. - IChemE	2.5	7.5	3.00
Seider et al. - Hand	2.5	7.3	2.92
Sinnott & Towler - IChemE	3.4	10.1	2.97
Sinnott & Towler - Hand	3.4	11.3	3.32
Average value [$\bar{\$}$]	**3.4**	**10.5**	3.18
Standard deviation [σ]	0.6	2.9	0.40
Coefficient of Variation [$\sigma/\bar{\$}$]	0.17	0.28	0.12

Many equipment types are present in this case as depicted in figure U.28, with the evaporator/dryer, storage vessels and mills representing the majority of investment. Figure U.30 shows a high amount of scatter in the equipment classes for solids handling (a bucket elevator), mills and filters. These categories proved to be difficult to estimate by Turton et al. and Sinnott & Towler, for the database was very limited in these classes. Woods is the most versatile containing many types of equipments and set-ups and may therefore be considered leading in this case. The high price for the dryer by Turton et al. is puzzling for no obvious reason may be pointed out, rather to be an inconsistency between databases.

The lack of a reference value results in a comparison made between estimation techniques only. The coefficient of variation is relatively high. Consequently based on the measurements it can be stated that with 95% confidence the actual value is between $4,700,000 and $16,300,000. The value is expected to be within $7,600,000 and $13,400,000 with 68% confidence.

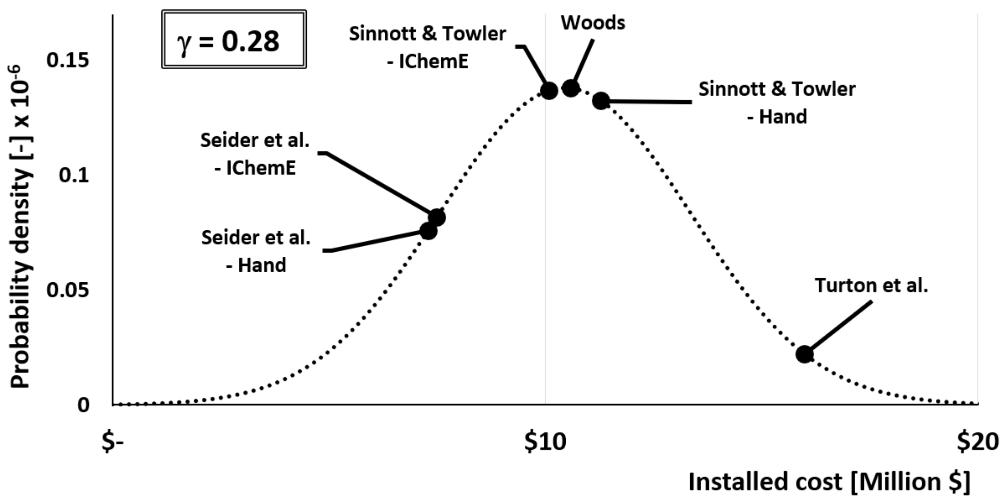

Figure U.29: The constructed normal distribution curve for case 10.

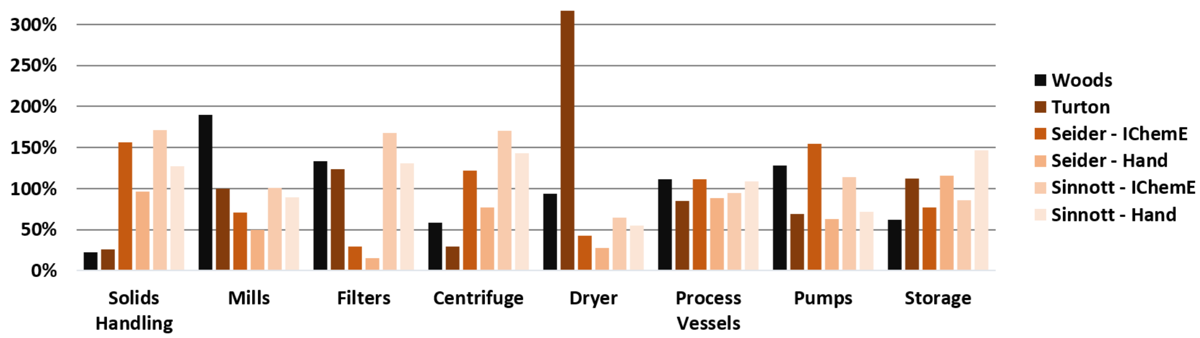

Figure U.30: The estimated value per equipment class, shown relatively to the average value (100%).

U.11 Case 11: Methylamines from Methanol and Ammonia

Case 11 is another project executed by students, Mansouri et al.[118], as a part of a design project. The aim was to develop a process to produce methylamines (mono-, di- and tri) from methanol and ammonia. The production target is a total of 165 tonne per day. No reference value was selected for the process may not be considered to be fully designed according to industrial standards. Therefore historical cost data would not match the design. The case however may therefore not be disregarded, it is still a tool to indicate differences between factorial methods.

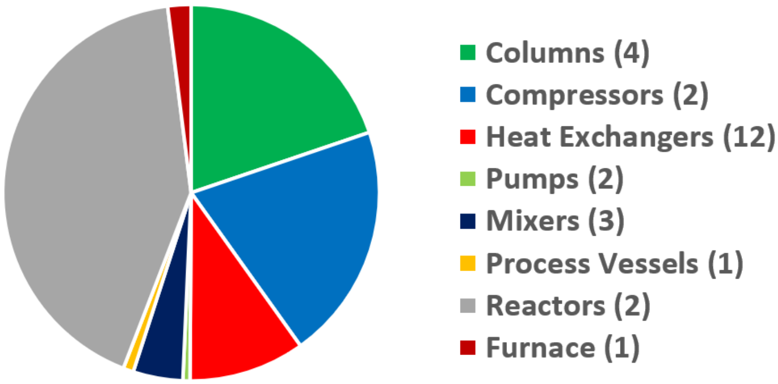

Figure U.31: Equipment mix of case 11 depicted as per dollar off the average values.

Table U.11: The results of applying the estimation techniques for case 11.

	F.O.B. price [M$]	**Installed BL price** [M$]	**Apparent Factor** [-]
Woods	4.5	11.4	2.53
Turton et al.	3.7	10.1	2.73
Seider et al. - IChemE	3.8	12.2	3.21
Seider et al. - Hand	3.8	11.3	2.97
Sinnott & Towler - IChemE	6.5	20.6	3.17
Sinnott & Towler - Hand	6.5	22.7	3.49
Average value [$\bar{\$}$]	**4.6**	**14.7**	3.02
Standard deviation [σ]	1.1	5.0	0.32
Coefficient of Variation [$\sigma/\bar{\$}$]	0.24	0.34	0.11

Figure U.31 reveals that the majority of cost are found in the reactors, compressors and columns. Figure U.33 shows that the agreement on column cost is high, whereas especially compressors are problematic. The high costs estimated by Sinnott & Towler on compressors is a returning issue. Combined with a high estimate on reactors results in the overall high value shown in table U.11 and figure U.32. The high value in Sinnott & Towler - IchemE's estimate for furnaces is due to a high factor value by the IChemE method. The low dollar value of the individual furnace produces a installation factor. The low value for process vessels by Turton et al. is a consequence of the fact that the correlation is based upon volume, while the other methods correlate to shell mass. Because volume scales differently than shell mass, results may deviate especially at the limits and indeed the process vessel is of a small size.

The coefficient of variation is still relatively high due to Sinnott and Towler's estimates being quite higher than the others visible in figure U.32. From the data points it may be concluded that with 95% confidence the correct value is between $4,700,000 and $24,700,000 battery limit investment cost. A 68% confidence interval is constructed between $9,700,000 and $19,700,000 dollar. This shows that the predictive value of this method is relatively low.

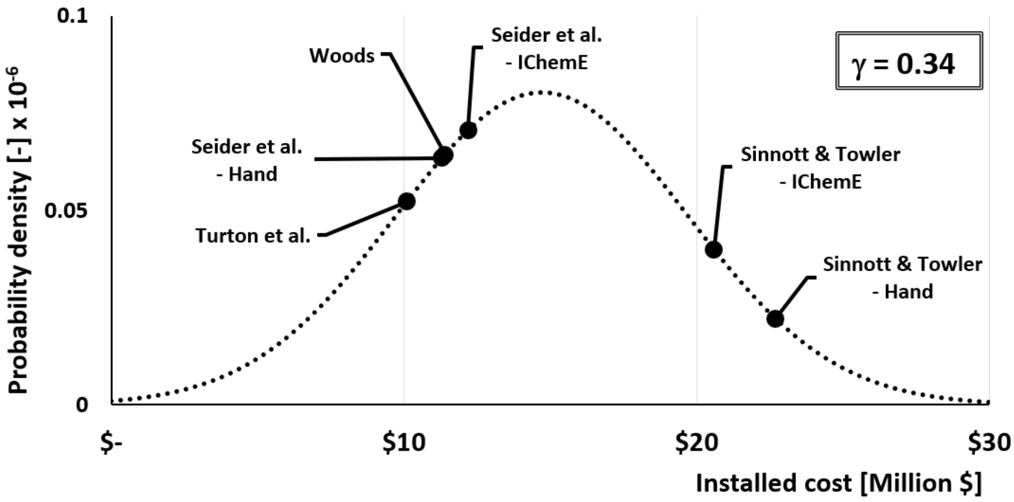

Figure U.32: The constructed normal distribution curve for case 11.

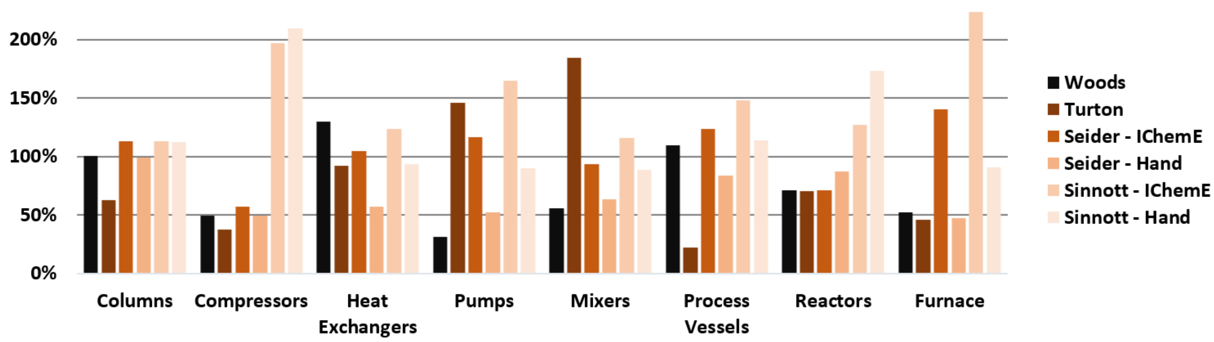

Figure U.33: The estimated value per equipment class, shown relatively to the average value (100%).

U.12 Case 12: Bio-ethanol to Ethylene

The bio-ethanol to methylene case is described in the work of Cameron et al.[119]. The battery limit investment is focussed on the conversion of ethanol to ethylene and is not considering the influence of the feedstock. The ethylene production is set at 3,800 tonne per day.

The reference value applied in this case is somewhat controversial. Two data points were acquired, one is the prediction by Cameron et al., the other comes from another bio-ethanol to ethylene research project in Brazil. It is published by Mohsenzadeh et al.[125] The correlated reference point is problematic for the battery limit investment cost found in from both sources are close in cost, but differ considerably in production capacity.

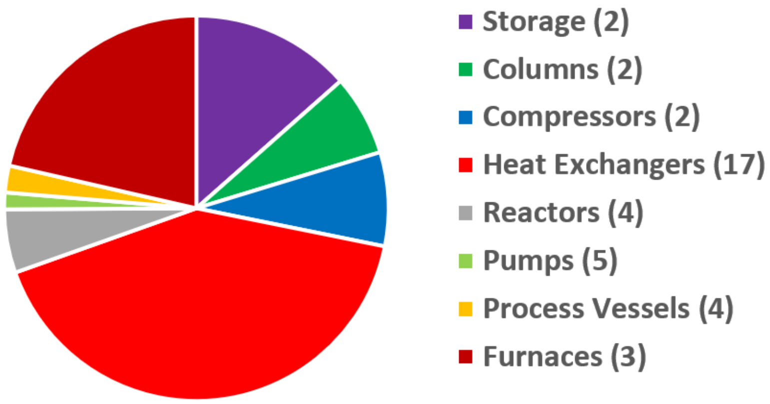

Figure U.34: Equipment mix of case 12 depicted as per dollar off the average values.

Table U.12: The results of applying the estimation techniques for case 12.

	F.O.B. price [M$]	**Installed BL price [M$]**	**Correction Error in BL Estimate [%]**	**Apparent Factor [-]**
Woods	14.5	36.2	+25%	2.50
Turton et al.	20.8	48.0	-5%	2.31
Seider et al. - IChemE	16.6	42.2	+8%	2.54
Seider et al. - Hand	16.6	39.2	+16%	2.36
Sinnott & Towler - IChemE	18.8	47.6	-5%	2.53
Sinnott & Towler - Hand	18.8	59.9	-24%	3.19
Average value [$\bar{\$}$]	**17.7**	**45.5**	**-0%**	2.57
Standard deviation [σ]	2.4	7.7		0.29
Coefficient of Variation [$\sigma/\bar{\$}$]	0.13	0.17		0.11
Reference Value		**45.4**		

As shown in figure U.34 the equipment mix is divers, with a large role for many smaller heat exchangers. Table U.12 and figure U.35 show a low coefficient of variation among methods and a very good correspondence with the reference value. However it should be noted that due to the unreliable background of the reference value no great merit may be adhered to the resemblance. At least all methods do coincide with the predicted value of Cameron et al.[119], indicating that the estimates are at least in the right order of magnitude.

Looking at figure U.36 the compressor estimate values of Sinnott & Towler again are significantly larger than those of the other methods. The categories for storage, columns and process vessels show a high similarity between methods.

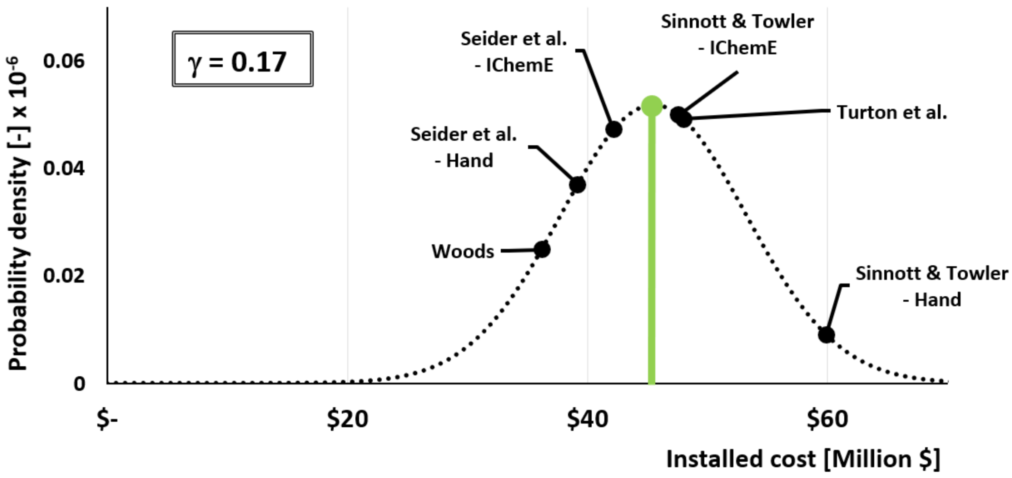

Figure U.35: The constructed normal distribution curve for case 12. The green line indicates the reference value.

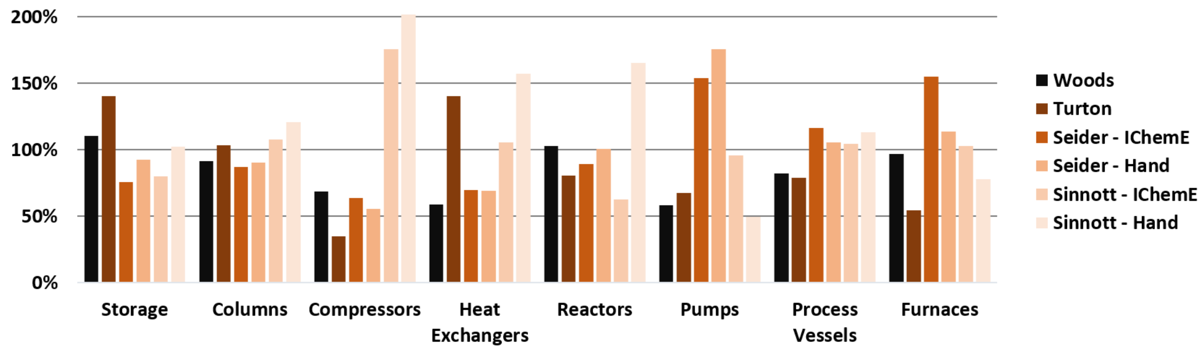

Figure U.36: The estimated value per equipment class, shown relatively to the average value (100%).