CHAPTER VIII

Refinery design

Refineries are complex systems and the relevance of "chaos" theory to the description of refineries has been pointed out. This served as a warning that a purely mathematical approach to refinery design may yield optimal theoretical designs, but not necessarily operable practical designs. A distinction has been made between conceptual and real-world refinery design. Whereas the development of conceptual refinery designs require only the feed description, product requirements and knowledge of the conversion processes, real-world refinery designs are also influenced by other aspects, such as the refinery location and secondary design objectives.

1. Introduction

It is quite possible to deal with refinery design in similar terms as any other discipline dealing with inputs and outputs, such as business planning, manufacturing design or even authoring. For example, most of the goals of software engineering(1) are equally applicable to refineries: low cost of production, high performance, portability (or flexibility in refining parlance), low cost of maintenance, high reliability and delivery on time. Although the analogy to refinery design is appreciated, no attempt will be made to repeat the reasoning that has already been properly documented in textbooks. In essence it is believed that refinery design is a creative process, that can be aided by a systems approach, but cannot be efficiently replaced by it.

In the Prologue (Chapter I) the importance of issues such as energy security and environmental impact have already been mentioned. Considering an investment in a refinery as a business decision with the sole objective of making money, is therefore patently wrong. To quote from a discussion on the nature of organisations:(2) "It often seems that organizations exist simply to make money, but in reality this is rarely the case, though, of course, money plays an important part". Not all refinery design decisions are subject to the engineering favourites, optimisation(3) and economic evaluation.(4) These two disciplines tend to reduce refinery flexibility, something that should not be done during the conceptual refinery design phase. It may lead to a wonderful refinery design on paper, but an untenable design in practice. The lessons that can be learnt from the wonderful book on Systemantics by John Gall(5) should not be lost on refinery designers – refineries are complex systems and subject to all the peculiarities associated with complex systems. The behaviour of complex systems is also closely linked to “chaos” theory, as illustrated by the well-known novels on chaos theory by Michael Crichton(6)(7): “Jurassic Park” and “The Lost World”. This field is considered so relevant that the introduction to refinery design is intentionally interrupted to emphasise this point. A simple mathematical example illustrates the potential impact of underestimating be behaviour of complex systems.

The Mandelbrot-set (Figure 1) is generated by plotting the number of iterations that is required for a simple equation (Equation 1) to reach a threshold criterion (Equation 2). The three-dimensional picture is represented in two-dimensions as a contour-plot of j for various values of c. The value of c, which is a complex number, is represented as x,y-coordinates with the real-value plotted on the x-axis and the imaginary-value plotted on the y-axis.

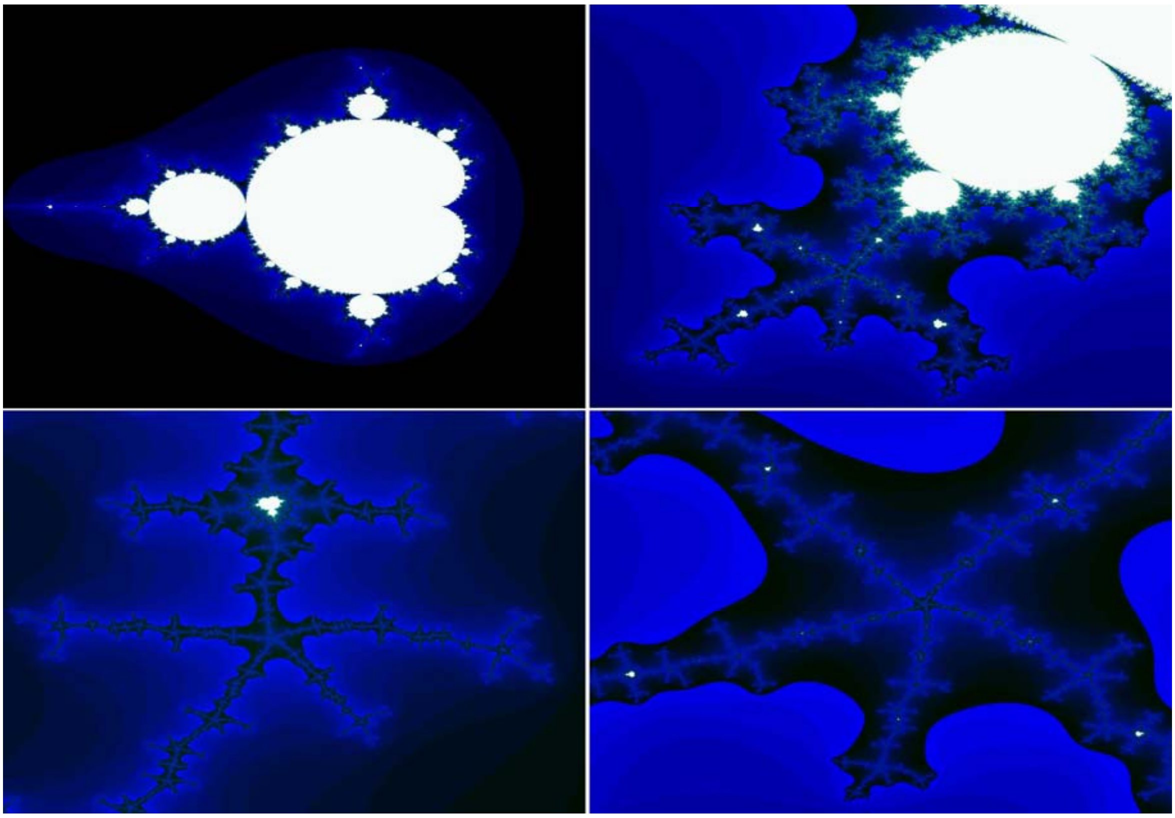

Figure 1. Mandelbrot-set showing the significant amount of variation, even when the zoom level is increased. Clockwise from the top left, the values of c being plotted are (-2+1.5i to 1-1.5i), (-0.65-0.51i to -0.45-0.71i), (-0.625-0.668i to -0.605-0.688i), and (-0.615-0.683i to -0.6137-0.6843i).

$$z_{j+1} = z_j^2 + c \qquad \text{... (1)}$$

$$|z_j| > 2 \qquad \ldots (2)$$

Despite the simplicity of the mathematical description, it is impossible to a priori predict the answer. Furthermore, even a small change in the value of *c*, can significantly change the answer, making even interpolation dangerous. There is beauty in Figure 1, but also a warning. Unless a refinery design is clearly in a stable region, small changes in feed composition or refinery operation may render the refinery inoperable. It is therefore recommended that refinery designs should have as little as possible complexity, with as much flexibility as it would allow.

The basic treatment of refinery design that is presented in this chapter focuses mainly on practical aspects and may not satisfy our more mathematically inclined brethren. The aim of this chapter is to specifically highlight the importance of design objectives and how these influence refinery designs. This does not imply that a more theoretical / mathematical based approach to refinery design is wrong. However, as already cautioned, a mathematically optimum refinery design runs the risk of being brilliant only on paper. A distinction is therefore made between conceptual refinery design and real-world refinery design.

2. Conceptual refinery design

Irrespective of the complexity inherent in refinery design, some basic steps can be identified that are common to all design approaches. In the development of any process configuration, three inputs are implicitly required, namely:(8)(9)

a) Feed description. This defines the nature of the feed material that will be refined.

b) Product description. Fuel specifications and the product slate required.

c) Processes. Conversion, separation and utility processes to be considered.

This effectively determines the scope of work for the project and contains sufficient information for the conceptual development of a refinery configuration. With this level of detail, only conceptual studies are possible. It is nevertheless useful, since it allows refinery design to be studied divorced from the factors influencing real-world refineries. In this way the limitations and sensitivities of different refinery designs can be probed, without getting bogged down in the additional complexity introduced by issues such as refinery location. This conceptual approach will be used in the next chapter to study Fischer-Tropsch refinery configurations.

It has already been noted that refinery design is essentially a creative process and that there are different tools and methodologies to guide this process. It is nevertheless instructive to look at some of the approaches that have more recently been followed for refinery designs:

a) *Linear programming*.(10) Design constraints such as fuel specifications and objective functions like minimum capital cost or highest distillate yield, can be incorporated in a linear programming model. This enables the solution of a complex optimising problem. However, it presupposes the development of multiple refinery configurations. Accurate modelling of the various refinery units is imperative to the success of linear programming.

b) *Hierarchical design*.(11) A design hierarchy (Figure 2) has been proposed for refinery debottlenecking, which can also be used to guide design. It is akin to the Michael Jackson programming approach,(1) were the data flow, “in” transformed to “out”, determine the structure of the design. In the hierarchical design approach, the feed flow is used to determine design bottlenecks and it can also be used for analysing sub-systems of the refinery. For example, hydrogen availability can be used to drive refinery design.(12)

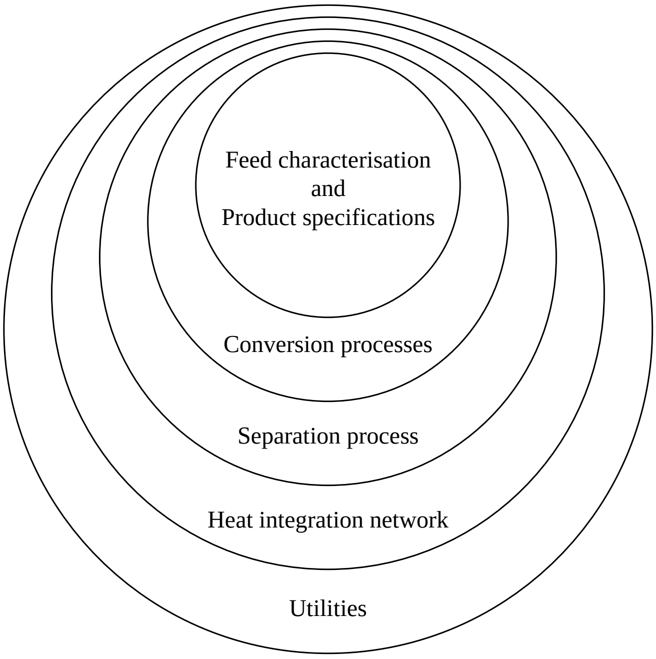

Figure 2. General refinery design hierarchy adapted from ref.(11).

c) *Technology pre-selection*.(13) An interesting approach to refinery design has been followed by Nai Y. Chen, one of the ZSM-5 pioneers at Mobil research. Refining technology has been pre-selected based on its environmental footprint and the refinery design was then done based on a logical ordering of the more limited set of technologies. A variation on this is to make use of pre-selection based on technology compatibility to the feed material.(14)

In all instances the design process relies on some underlying refinery design logic that has to be applied. The logic being referred to, is the logic associated with the knowledge of different refining technologies, their feed requirements and their objectives. This has been discussed in the previous chapter (Chapter VII). For example, when a heavy paraffin cut has to be refined, it is logical to look at separation technologies and residue conversion technologies first, while olefin upgrading technologies can be ignored.

3. Real-world refinery design

Real-world refinery designs, as opposed to conceptual studies, have the aim of producing a practical refinery design for a specific purpose. There are many factors influencing real-world refinery designs and when this added layer of detail is considered in the design process, the design becomes unique. It should be emphasised that beyond the conceptual stage, there is no such thing as a generic or even general refinery design, despite many real refinery designs being close to each other.

In this section some of the important factors affecting real-world refinery designs are discussed. It will be shown that this is not just an added layer of detail that is superimposed on the conceptual refinery design, but that it dictates the design by influencing the feed and product description, as well as the process selection. The arbitrary feed, product and process selection that can be made during conceptual designs now becomes a requirement or consequence of factors such as location, market and politics.

3.1. Refinery type

The selection of refinery type is a business decision and constitutes the *primary design objective*. There are three main crude oil refinery types, namely fuels (energy refinery), petrochemicals and lubricants (non-energy refineries).(15) It is also possible to combine these different refinery types to yield a mixed-type of refinery that could have some economic benefits.(16) The decision nevertheless remains one made by the business as an investment decision that fits into its overall business strategy.

3.2. Products and markets

The type of products and the market into which the products will be sold, forms part of the business decision to build a specific type of refinery. The identification of a market gap, or strategic positioning within a specific market may drive this investment decision. The products and markets should be considered together, since the products determine what will be made, while the markets determine the product specifications.[a] For example, a refinery producing fuels for the current Central African market will look considerably different to a refinery with the same product distribution but targeting the European market a decade into the future.

In principle all refinery designs should aim to meet a future demand in a market requiring future fuel specifications. Anticipating changes in fuel specifications is therefore not merely a mental game, but could have a huge impact on the cost and complexity of a refinery design. This places the discussion on future trends in fuel specifications (Chapter II) into perspective. It is inevitable that there will be a number of years' difference between the time at which the refinery design is frozen and the time when the refinery has been constructed, commissioned and is in production. The importance of refinery design flexibility cannot be over emphasised, since it is almost inevitable that the refinery will have to be modified in some way during its existence to keep up with changes in fuel specifications.

3.3. Feedstock

In a crude oil refinery the feedstock, or basket of crudes that is selected, has a significant impact on the profitability of the refinery. The range of crudes that can be processed is determined during the refinery design phase and flexibility to deviate from the design basis is determined by processing constraints. For example, if the distillation units were designed for Arabian Light (54% <350°C material), it is quite possible to exchange it with crudes such as

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[a] Understanding the market may in some instances be much more than adhering to or anticipating specifications. This is especially true of speciality markets for petrochemicals, but may also be true of fuels. A classic example can be found in the history of the oil industry. When Marcus Samuel (founder of Shell) took on Standard Oil (of John D. Rockefeller) in the Far East, the plan hinged on the efficiency of shipping kerosene in bulk, rather than in tins that had to be packed in wooden cases (both the tins and wood being expensive). However, when the kerosene was placed in the market at half the cost of Standard Oil's, nobody wanted it. It turned out that the tins played a vital role in the Far Eastern way of life, since the tins could be re-used for the manufacture of household items like buckets, cups, etc. The tins were therefore more important to the market than the kerosene! See ref.(17) pp.48-49.

Iranian Light (55% <350°C material), but not with Algerian Hassi Messaoud (75% <350°C material) or South American Bachequero (30% < 350°C material).(15) The price differential between low quality heavy crudes and good quality light crudes can exceed US$ 10 per barrel, but the refining infrastructure and operating cost required to process poorer crudes may not justify the selection of cheaper feed.(18)

Since the nature of the feedstock determines the refining effort to produce the required product slate, care should be taken to match the feedstock to the product requirements. For example, it would make better sense to select Venezuelan Tia Juana or Bachequero crudes that naturally yield good lubricating oil properties as feed for a lubricant refinery, rather than selecting a crude oil that requires significant processing to achieve the same result.(19)

It may also happen that exploiting a specific feedstock is driving the decision to build a refinery. This typically happens when energy security features on the political agenda of a country. This is especially true of coal-to-liquids facilities, where energy security issues require a specific type of feedstock to be used. Likewise, when the scare of global warming requires a renewable energy source to be selected, biorefineries leap to mind.(20) In such cases the feedstock is pre-selected and is the driver for the refinery design, rather than a marketing opportunity or specific product demand.[b]

In a Fischer-Tropsch refining environment the feed material has less of an impact on the refinery design. Irrespective of whether it is a biomass-to-liquids (BTL), coal-to-liquids (CTL) or gas-to-liquids (GTL) facility, the feed is first converted to synthesis gas, thereby making all feed materials equivalent. It is therefore the choice of Fischer-Tropsch technology that determines the properties of the syncrude that has to be refined, not the feed. However, the properties of the feed may still influence the refinery design in an indirect manner. For example, if the coal requires low temperature gasification, some tar pyrolysis products will be co-produced, which in turn will require tar refining to be included in the overall refinery design. Similarly, the gas used in a GTL process may have some associated condensates, which requires co-processing in the refinery. Some of these integrated refinery scenarios have been explored previously.(14)

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[b] A word of caution is prudent. When a refinery is designed on political preference or based on a trend, it is critical to ensure that the design is robust enough to weather a reversal in political opinion or change in trend. For every trend there is a potential trend killer. It may be easy to spot the trend, but not always so easy to spot the trend killer. For example, with instability in oil supply, coal-to-liquids becomes fashionable as means of energy security, but the trend killer is the perceived link between CO_2 emissions and climate change.

3.4. Location

The importance of selecting the location of the refinery is like the three P's of property investment – "position, position and position". Generally refineries are located close to the source of the feedstock, or on trade routes with easy access to feedstock. Most crude oil refineries are consequently situated at the coast with easy access to shipping for supply of feed and export of product. Inland refineries are less common and require either a local feed source, or access to a pipeline for supply. In the case of Fischer-Tropsch based refineries it has thus far been the practise to situate the facility close to the feed source. Solids handling is generally more difficult and expensive than fluids handling, making it almost imperative to situate CTL and BTL refineries close to the source of the feedstock. The same applies to GTL refineries, since GTL facilities need to compete with liquefied natural gas (LNG), which is effectively the transportation alternative.

Yet, in selecting a location there are other aspects to consider that may outweigh positioning the refinery based on feedstock only. The location impacts directly on the refinery design and operation in terms of design details and cost. Some of these location specific aspects to consider are:

a) *Climate*. This determines the insulation, heating and cooling requirements. In extreme climates, such as found in the Arctic, or Middle Eastern desert, special measure may be required to deal with either heating or cooling.[c] The material of construction is also influenced by the climate, with atmospheric corrosion in coastal regions generally being higher than for inland locations. The recent spate of hurricanes in the Gulf of Mexico also illustrated the potential effect of extreme weather phenomena on refineries.(21)

b) *Geology*. The geology of the refinery site may require special measures to be taken in site preparation and construction. Examples of such measures include the strengthening of foundations for earthquake protection and the use of deep foundations in marshy ground to ensure that construction is supported by bedrock.

c) *Natural resources*. The lack of sufficient water or water of acceptable quality to make use of a standard cooling water design, may add to the refinery cost. For example, refineries in the Middle East generally employ salt water cooling systems.

d) *Environmental sensitivity*. Working in a sensitive ecology can markedly affect construction and operating practices. This is also true of facilities that are situated close to communities. It may be required to use quiet rotating equipment, ensure that emissions[d] are lower than legal limits and invest in plant beautification. Construction in such areas needs to be especially well-planned, since future expansion possibilities might be limited. Future site remediation and environmental impact of operations may dictate some design decisions, such as on-site effluent treatment and investment in low emission technologies only.

e) *Utility access*. Power and potable water may not be readily available. In locations where the power grid is already taking strain, it may be prudent to invest electricity generation. In remote areas where potable water supply and sewerage works are not available, construction of such utility systems may have to be undertaken.

f) *Location factor*. Cost estimators use the location factor as a measure to indicate the impact of the location on the construction cost. The location factor tends to be higher for inland locations and locations far from a significant skills base. If the refinery is not situated close to a commercial harbour with the infrastructure to off-load large vessels, the supply and transport of equipment can become an issue. Unit sizes may have to be restricted to facilitate road transportation and it will also impact the construction schedule. Although this might seem like a once off impact, it is not. Siting a refinery in a remote location where living conditions are not considered desirable can result in a much higher operating cost too. It may be necessary to pay more for labour (need for “location allowances”), work force productivity may be lower and it may also be more difficult to attract and retain skilled personnel.[e] It may even be necessary to establish new towns.

g) *Legislation*. Refinery design is subject to various laws, such as the environmental legislation. This may require investment in technologies for CO_2 sequestration or even prevent the use of some technologies, such as HF alkylation. The intellectual property protection provided by the legislature is also an important consideration, since inadequate licensor protection might limit the basket of technologies that can be licensed for the refinery design. Legislation will also govern future operation of the refinery, noting that the profitability of the refinery will be affected by labour laws, tax laws,(23) competition laws, etc.

h) *Politics*. The local, national and international politics of the region could have an impact on the refinery design. Preferred suppliers and boycoting of suppliers will affect the technology selection. Global politics may also influence the refinery design. For example,

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[c] These measures transcend the equipment design. For example, the lubricating oils for rotational equipment needs to be suited for the climate.

[d] Communities may even rebel at perceived emissions, such a steam.

[e] This can be a very serious consideration. The significant performance deterioration seen at Sasol 1 after 1976 has been directly attributed to the loss of key personnel to the Sasol 2 and 3 projects. Ref.(22)

the United States government placed restrictions on the supply of technology to countries like Iran, which implies that a refinery design for Iran will be limited in its technology selection. Other issues that may affect refinery construction and operation include security, crime, labour unrest, government integrity and local bribery practices.

i) *Marketing logistics*. Although the product and market selection can be done independently of the refinery site selection (product can be exported), the latter will impact the refinery design. The location will impart a location advantage or disadvantage for the different products. For example, a fuels refinery close to an international airport will have a location advantage for jet fuel, which will outweigh that of diesel fuel, with its more diffuse market distribution and a refinery design favouring jet fuel over diesel fuel production would make more sense. The refinery configuration is not only affected by the market for final products, but it may also be affected by the market for intermediates and blending components. When a refinery is close to other refineries and petrochemical producers, business agreements can be put in place to simplify the refinery design. By inter-refinery exchange of intermediate products, which cannot be sold to consumers, final products can be prepared by blending. In this way refineries can decrease the capital investment required to refine products to specification. It may also be beneficial to deliberately sell a specific product as an intermediate, rather than refining it at all. For example, the Oryx GTL facility in Qatar produces a Fischer-Tropsch naphtha that is not refined to motor-gasoline, but rather sold as naphtha feed to the nearby naphtha crackers. Conversely, when the refinery is far from petrochemical markets, it may be necessary to convert high value olefins such as ethylene and propylene into fuel. In a Fischer-Tropsch refinery the same may apply to the reaction water oxygenates.(24) Transportation of reactive intermediates over long distances could also present problems, with routing being dictated by local legislation and possibly the need for re-purification closer to the market.[f]

j) *Patents*. Unless protection for a technology is filed very widely, some countries may have been omitted. The presence or absence of relevant patents in a specific country may either create an opportunity or provide an obstacle to the refinery design. This is especially relevant to Fischer-Tropsch refining, where “freedom to operate” in South Africa is virtually guaranteed by the commercial South African Fischer-Tropsch refineries. This is not true in other countries, where the patent landscape is more involved.

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[f] Transportation of carcinogenic substances such as benzene might be prohibitively expensive and routing benzene through some countries may even be illegal. Other chemicals may have insufficient storage stability and require re-purification, such as 1-pentene for co-monomer use.

3.5. Secondary design objectives

The importance of *secondary design objectives* should not be underestimated, since it is these objectives that influence the details of the design. These should be set by the business to guide the refinery design to meet the current financial situation, strategic direction and even to reflect the corporate culture. Examples of such secondary design objectives, sometimes erroneously called a “wish list”, are:

a) *Minimise capital expenditure*. This directive is necessary when the gearing of the company is high and additional capital cannot be raised through share issues. The impact of this on a refinery design is to invest in the least expensive configuration that will meet the primary design objective. Typical side-effects of spending the least amount of capital are reduced flexibility (more units operating at or close to nameplate capacity), increased operating cost (more labour intensive units with less automation[g]), reduced on-line availability (less redundant equipment, such as spare pumps) and increased maintenance cost (less expensive materials of construction and quality of equipment).

b) *Maximise nett present value (NPV)*. In a refinery there is a limited refining margin available to generate profit and in a regulated environment, like South Africa, there is a fixed difference between the feedstock cost and the product price. Any capital spent on the refinery to keep up with changing fuel specifications, per definition has a negative NPV. Such expenditures are seen as part of the cost of staying in business. The NPV can only be positively affected if the yield of final products per unit volume of feed is increased, a cheaper feed stock can be used to produce the same products, or the product slate is changed to contain more high value products. In this respect the options open to the refinery designer are limited by the limitations placed on the refinery type, feed selection and product slate. Generally the highest NPV can be obtained by producing more non-energy products, such as chemicals.

c) *Smallest environmental footprint*. It is wrong to state that more environmentally friendly technologies cost more, although they generally do. In the previous chapter (Chapter VII), the environmental impact of refining technologies were discussed and it should be clear that there are often more than one way to achieve a specific outcome during refinery design.

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[g] The level of automation is a detailed design issue, but some technologies lend themselves to a low degree of automation (like hydrocracking), while others demand a high level of automation (like FCC).

Environmentally friendly design is part of responsible engineering and it should always be a design objective.

d) *Maximum liquid product volume*. In fuels refining this strategy often forms the basis for maximising refinery profitability. Fuels are sold by volume and an increase in the volume of final products per unit volume of feed generally translates into increased profits. This will drive refinery technology selection away from conversion processes that reduce the liquid volume of products and will tend to drive refinery design to maximum motor-gasoline production. In instances where the product slate definition leaves little leeway for a shift to motor-gasoline, the refinery design will tend to focus on hydrogen addition processes, since these would reduce the density and increase the volume of products. Focussing on maximum product volume may also drive refinery design to increase investment in processes for the conversion of light olefins to fuels, such as olefin oligomerisation, etherification and aliphatic alkylation.

e) *Refinery flexibility*. Energy markets are cyclic, as typified by the "summer driving season" and "winter heating market". The same holds true of chemical markets. Refineries are therefore exposed to these variations. It is a business decision whether it its better to invest in the capital necessary for refinery flexibility, or whether the production surplus will rather be sold at discounted prices. Investing in refinery flexibility also has other benefits, namely, that it will be easier to meet future specification changes (smaller chance of specific units constraining refinery upgrades), plant upsets are easier to deal with (re-routing of streams is possible) and plant shutdowns are less constraining (more capacity to work away product). However, added refinery flexibility may come at the cost of added complexity, but this is not necessarily the case.

f) *Least refinery complexity*. The most elegant refinery designs are those where the refinery has the most flexibility with the least complexity. Unfortunately "complexity" can be an ambiguous term and should be defined. Cost estimators define complexity in terms of the type and/or number of units in a plant or refinery, which can then be used to estimate the capital cost.(25)(26) Although this may sound like a sensible definition for capital cost estimating purposes, it does not capture the interdependency of units and amount of work performed (operating cost) to make a final product. It is suggested that refinery complexity should rather be expressed in terms of the number of refinery units a molecule visits before ending up as a final product. This definition is a measure of the refining efficiency (rather than size), since it is a measure of how much work is performed on a molecule before it can be sold. Such a definition would imply that a refinery with more units, but less inter-unit transfers is less complex than a refinery with fewer units, but more inter-unit transfers.[h] Using this definition it implies that refinery complexity can be reduced by proper molecule management (efficient design),[i] which ensures that the feed to each separation and conversion unit is well matched to that unit. Because this definition gives an indication of inter-dependency, it follows that refinery stability increases with decreasing complexity (an upset in one unit is less likely to affect the operation of the other units). A reduction in refinery complexity therefore has a positive impact on the operability of the refinery, although it may not necessarily imply that the refinery has less units, or that it is a cheaper refinery design to construct. However, it does imply that the cumulative capacity of all units on a feed basis will be less for a refinery with a lower complexity.

g) *Shortest time to completion*. Time pressure on the project schedule is driven by economics, which may be linked to a transient window of opportunity. Whatever the business reason, the construction schedule of a refinery can only be reduced by selecting commercial technologies with a low construction (not refinery) complexity. Technologies requiring specialised manufacturing, exotic materials or highly skilled artisans to construct are automatically disqualified from the design.

3.6. Other issues

Refinery designs may be influenced or restricted by other issues too. Foremost amongst these are agreements and intellectual property rights. Instruments for the protection of intellectual property rights, such as patents, may preclude the use of specific technologies. Conversely, agreements, such as joint ventures, may lock the refinery design into the use of specific technologies. For example, Sasol has a joint venture agreement with Chevron that necessitates the use of Chevron hydrocracking technology for all GTL refineries.

Likewise there may be contractual obligations and restrictions that may lock the refinery production into a specific market or out of a market. For example, until December 2003 the Sasol Synfuels refineries were locked into a supply agreement with the other oil companies in South Africa. On termination of that agreement, the Synfuels production

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[h] In mathematical terms this can be expressed using digraph theory. Ref.(27) If the refinery is represented as a weighted digraph, the weighted indegree of each node (refinery unit) can be calculated (sources and sinks are excluded from this calculation). The refinery complexity can then be expressed as the average indegree per node divided by the cumulative outdegree of all sources.

[i] Molecule management relies heavily on proper separation. Sloppy separation can cause increased refinery complexity or decreased refinery efficiency, because some molecules are routed to the wrong units. This may even necessitate pre- or post-treatment steps that could otherwise have been avoided.

volumes were no longer restricted, but they were no longer guaranteed of a market either. With no guaranteed market, it was found that the motor-gasoline to distillate ratio produced by the refinery was not aligned with the product ratio that could be sold into the local market.

There may also be licensing limitations. The licensors of technologies may have reasons for not licensing their technology for a specific application or to a specific company. This will restrict the refinery design, especially if it is a key technology that cannot be licensed and where there is not an equivalent alternative technology that can be licensed instead.

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