ABSTRACT

The design of concentrators is driven by a number of factors, including:

- ore characteristics and resultant process design criteria and flowsheet;
- location, altitude and climate;
- terrain and ground conditions;
- construction approach;
- maintenance strategy;
- local design standards, and
- experience and “baggage” from previous projects.

This paper will discuss how these factors impact on plant design and capital cost using specific examples from concentrators constructed in Australia, Asia and Africa.

The ore characteristics and process design inputs are a function of geology and good metallurgical practices. As such, these critical design inputs should be common to all design outcomes for a given project, irrespective of location. However, interpretation of the design inputs and criteria can lead to variations in process flowsheet that impact on design layout and plant capital cost. In the main, these variations relate to simplification and/or optimisation of the flowsheet.

The impacts on plant design due to location, terrain, altitude and climate are substantial. Whilst flat sites simplify design and construction, they can add capital cost due to the need to elevate equipment to optimise operating costs. Steep sites and/or poor geotechnical conditions add substantial cost to site earthworks but operating and maintenance costs can be minimised by gravity flow.

Cold climates and elevated sites add cost due to the need to have most of the plant enclosed and generally protected from the elements, adding substantial cost. Similarly, tropical climates may require protection from sun and heavy rain.
For plants that are not constructed within buildings with overhead gantry cranes, i.e. "open-air", the maintenance and construction approach can have a large impact on design, schedule and cost. For "open-air" plants, the use of mobile cranes, gantry or portal cranes and tower cranes for plant maintenance will impact on plant layout and footprint. For example, the use of mobile cranes for maintenance can often increase the plant footprint or sacrifice access, with consequential increase in capital cost for services.

Experience from previous operations and projects plays an important role in equipment selection and layout. Typically, this falls into three categories:

- insight and experience that should be included due to the value added to the project;
- “wish list” items that assist in operation and maintenance of the plant, and
- “baggage” that can adversely impact on project outcomes.

Assessing the value of design alternatives or potential changes to plant design can be heavily impacted by the qualitative and semi-quantitative inputs making definitive assessment of value over life of business an intuitive process. Similarly, assessing the value of new ideas and innovation can be difficult due to existing paradigms and the risks associated with the unknown.

This paper expands on the above topics and provides specific examples of where different approaches have been used to address similar circumstances and some of the pros and cons of these approaches.

**INTRODUCTION**

Ausenco has designed and constructed concentrators in Australia, Asia and Africa for a range of clients. The more recent of these projects have included the:

- 20 Mt/a Lumwana copper concentrator in Zambia, and
- 12 Mt/a Phu Kham copper/gold concentrator in Laos.

In addition, numerous studies have been completed on concentrators of similar scale.

These projects and studies have been for a combination of junior and medium sized mining company clients. The plant locations are often remote, with some projects presenting significant supply and logistics issues.

In all projects, Ausenco has aimed to provide the owner with a “fit for purpose” plant. On some occasions this has involved detailed input from the owner based on their past operating and maintenance experience. However, for junior mining companies the constraints of project funding typically requires a strong focus on minimising capital costs in order to maximise project net present value and improve funding options.

The capital cost of a project is defined by numerous factors, some inherent in the ore body and/or location and others a function of approach that is adopted. The ability to impact on the project and design concepts and the resultant capital cost diminishes rapidly through the project assessment process (Figure 1).
WHAT DRIVES PLANT DESIGN AND LAYOUT?

The design and layout of a concentrator is based on a number of factors, including:

- ore type and processing requirements;
- flowsheet and equipment selection;
- mine life;
- site topography;
- site geotechnical issues, terrain and ground conditions;
- location, altitude and climate;
- environmental concerns;
- owner’s previous experience, preferences and risk profile;
- engineer’s previous experience and preferences;
- operator and maintenance access;
- operating and maintenance labour costs and skill level;
- construction approach and ease of construction;
- future expansion plans, and
- capital sensitivity.

Figure 2 illustrates the flow-on effect from design inputs to project outcomes. The following discussion highlights the dominant issues for each of the above factors.
Figure 2: Relationship between design inputs and project outcomes

**Ore type and processing requirements**

The fundamental design inputs for concentrators are a function of the ore type and the metallurgical testwork which are interpreted by the process engineer to provide the design criteria and process flow diagrams. Many papers have dealt with this process and the reader can refer to these for concentrators [Lane et al 2005, McLean, 2004, and Mullar, Halbe and Barratt, 2002], as necessary. Whilst testwork methods may differ, good metallurgical practice should lead to common design criteria irrespective of the location of the project and other attributes of the project.

**Flowsheet and equipment selection**

For the purposes of this discussion, we will assume that the design case is a copper porphyry ore and that the testwork and associated analysis has indicated that a conventional 10 to 20 Mt/a concentrator is appropriate, consisting of:

- crushing;
- stockpiling and reclaim;
- grinding;
- flotation;
- concentrate dewatering;
- tailings thickening, and
- process services (air, water and power).

There are variations on the conventional flowsheet that impact on design and layout, some of which are summarised in Table 1. These variations have very little inherent macro impact on plant layout after the ball mill and classification circuit. However, the front end ROM pad and crushing, HPGR or SAG mill and stockpile stacker type all have a significant impact on design footprint, plant layout and capital cost. The rise in the use of the SAG or AG mill circuit was based on the inherent simplicity, smaller footprint and lower capital cost of this circuit when compared with a multistage...
crushing circuit, for large concentrators in particular. As the size and capacity of cone crushers has increased and knowledge of HPGR performance has developed to provide a viable alternative to cone crushing, these differentials have reduced but are still significant.

From a technical development perspective, the focus is now on finding an acceptable HPGR flowsheet that minimises the need for screening and circulating oversize.

Table 1: Some flowsheet options by unit process

<table>
<thead>
<tr>
<th>Unit Process</th>
<th>Conventional Approach</th>
<th>Alternative Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crushing</td>
<td>Primary gyratory</td>
<td>Primary gyratory and secondary cone</td>
</tr>
<tr>
<td>Stockpiling</td>
<td>Conical stockpile</td>
<td>Ore stacking (travelling or slewing)</td>
</tr>
<tr>
<td>Reclaim</td>
<td>Apron feeders</td>
<td>Belt feeders</td>
</tr>
<tr>
<td>Grinding</td>
<td>SAG / ball mill (&amp; pebble crushing)</td>
<td>HPGR / ball mill</td>
</tr>
<tr>
<td>Flotation</td>
<td>Forced air cells</td>
<td>Self aspirated cells, column cells, other types</td>
</tr>
<tr>
<td>Concentrate dewatering</td>
<td>Thickener and pressure filter</td>
<td>Thickener and vacuum filter</td>
</tr>
<tr>
<td>Tailings thickening</td>
<td>High rate thickening</td>
<td>Conventional, high density or paste thickening</td>
</tr>
<tr>
<td>Process services (air, water and power)</td>
<td>Function of the above</td>
<td>Function of the above</td>
</tr>
</tbody>
</table>

Mine life

The mine life is determined by a number of factors, for example:
- size of mine reserve;
- optimum mining rate;
- duration of project life required for financing;
- economies of scale;
- capacity of the owner to develop the project
- ability of project infrastructure to service the project and associated cost increments, and
- cost increments driven by equipment capacity and step changes in associated cost.

The over riding factors for determination of mine life are the size of the reserve and the capacity of the owner to fund and market the project.

The mine life can impact on the evaluation of design options. Operating, maintenance and sustaining capital costs become more important project drives as the mine life increases.

Site topography

Site topography is inherent to each project. One of the usual characteristics of an Australian or African site is that there is generally little or no relief on the site. Asian locations generally have more complex terrain that can work in favour of gravity flow without having to elevate the head of
the circuit on concrete or steel structure. However, complex terrains may require complex earth retaining structures which can reduce this benefit.

**Site geotechnical issues**

Geotechnical conditions impact on earthworks and civils requirements and thus impact on detailed design and bulk materials requirements (capital cost). Lack of geotechnical data during a feasibility study can lead to inadequate definition of establishment and foundation works. The issues are common to most flowsheets and specific for each site.

**Location, altitude and climate**

Location, altitude and climate play a significant role in plant design. Africa, Australia and Asia have similar requirements with respect to temperature variation and climate (even the Australian outback has torrential rain events albeit very occasionally). The requirements of terrain and seismicity in Asia tend to be more akin to some Chilean conditions with moderate slopes leading to increased emphasis on earthworks for site preparation and increased civil and structural works.

**Environmental concerns**

The environmental constraints of the project with respect to dust, noise, water, wildlife, fauna and social impact can all have a significant influence on the location and layout of the project and plant. The need for plant within buildings may be a local requirement to satisfy noise or other environment regulations (eg. Cadia). Dust control, water availability and the need for water recovery can play a significant part in process selection, plant design and site layout and footprint, particularly in Australia.

**Owner’s previous experience, preferences and risk profile**

There are two extremes of owner’s experience (and subsequent preferences). At one extreme, junior resource companies typically target getting the project constructed and operational within a defined (and constrained) budget, and sometimes on a lump sum basis.

At the other extreme, large established companies with extensive operating experience place more emphasis on “life of project” issues and “life of project” optimisation. This can lead to a lot of input from the client’s team of plant operators and design engineers to the plant design process. Operator input is essential, but if uncontrolled can lead to significant negative impacts on schedule and costs due to conflicting focus and goals (Table 2).
Table 2: Comparison of Operator’s and Project Management focus on outcomes and approach

<table>
<thead>
<tr>
<th>Key Indicator</th>
<th>Operations</th>
<th>Project Management</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost management</td>
<td>Incremental costs – look at cents per unit</td>
<td>Spending big amounts quickly</td>
</tr>
<tr>
<td>Key driver</td>
<td>Expenditure (budget)</td>
<td>Commitment (contract)</td>
</tr>
<tr>
<td>Systems and procedures</td>
<td>Suit non capital works</td>
<td>Suit capital works</td>
</tr>
<tr>
<td>Time management</td>
<td>Driven by changing priorities, annual budget and fire fighting culture</td>
<td>Schedule driven and time critical</td>
</tr>
<tr>
<td>Management focus</td>
<td>Maintenance and operations focus. Micro management is the norm</td>
<td>Big picture management essential</td>
</tr>
<tr>
<td>Design focus</td>
<td>Operations and maintenance focus. Want “Rolls Royce” due to ease of operation and maintenance</td>
<td>Should provide “Fit for Purpose” facilities. Often “What we did last time”.</td>
</tr>
<tr>
<td>Cost focus</td>
<td>Not responsible for Project Costs</td>
<td>Responsible for Project Costs</td>
</tr>
</tbody>
</table>

The level of input from the project owner varies based not only on their operating experience, but also as a function of the owner’s team’s experiences. Junior mining companies typically have smaller owner’s teams (< five people) and rely on the engineer to deliver a “fit for purpose” product, particularly where a lump sum turn key (LSTK) approach to contracting is used. Large mining companies may have substantial owner’s teams (say > forty people) and as a result most aspects of the project are reviewed by the owner’s team members resulting in the style of the project reflecting owner’s team preferences as well as increased engineering costs as the various options are discussed, distilled, evaluated redone.

In general, both operator and owner’s team inputs increase capital costs and duration of plant construction particularly if the engineer’s team is inexperienced or poorly aligned with the owner’s requirements. The argument in favour of this process is that the resultant plant should have a lower life of mine cost.

**Engineer’s previous experience and preferences**

All engineering companies come with a history of design and approach that has a strong influence on the outcome. Even at a macro level, a pictorial review of concentrators throughout various regions will result in the identification of common layout and design approaches that point to the engineering company or group of origin.

Recent Australian concentrators such as Telfer, Cannington, Century, Cadia/Ridgeway and Boddington should have as many differences as similarities in that the designs and layout are born of the different engineering companies (i.e. GRD Minproc, Lycopodium, Hatch, Bechtel, Aker Kvaerner), clients and the differences in flowsheet requirements. However, only the Cadia/Ridgeway complex has a grinding circuit in a fully enclosed building and this was due to environmental aesthetic/noise reduction reasons. Some aspects of the designs are tabulated in Tables 3 and 4.
Table 3 Grinding Circuit Design Characteristics

<table>
<thead>
<tr>
<th>Circuit / Engineer</th>
<th>Building / Layout</th>
<th>Maintenance Factors</th>
<th>Approx Bulks¹</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Concrete (m³/kW)</td>
</tr>
<tr>
<td>Telfer / Minproc, Lycopodium, Hatch</td>
<td>External, 2 SAG &amp; 2 ball mills</td>
<td>Mobile crane &amp; drive-on grinding floor</td>
<td>0.21</td>
</tr>
<tr>
<td>Ernest Henry / Fluor Daniel</td>
<td>External, SAG and ball mill</td>
<td>Semi-portal crane</td>
<td>0.29</td>
</tr>
<tr>
<td>Cannington / BHP</td>
<td>External, SAG mill</td>
<td>Portal</td>
<td>NA</td>
</tr>
<tr>
<td>Century / Bechtel</td>
<td>Roof, SAG &amp; ball</td>
<td>Gantry crane</td>
<td>0.25</td>
</tr>
<tr>
<td>Cadia / Minproc, Bechtel</td>
<td>Internal, SAG and 2 ball mills</td>
<td>Gantry crane &amp; drive-on grinding floor</td>
<td>0.25</td>
</tr>
<tr>
<td>Phu Kham / Ausenco</td>
<td>External, SAG and ball mill</td>
<td>Tower crane &amp; drive-on grinding floor</td>
<td>0.2</td>
</tr>
<tr>
<td>Lumwana / Ausenco, Bateman</td>
<td>External, SAG and ball mill</td>
<td>Mobile crane</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Table 4 Flotation Circuit Design Characteristics

<table>
<thead>
<tr>
<th>Circuit</th>
<th>Building / Layout</th>
<th>Maintenance Factors</th>
<th>Cell Supports</th>
</tr>
</thead>
<tbody>
<tr>
<td>Telfer</td>
<td>External</td>
<td>Mobile crane</td>
<td>“Mushrooms”</td>
</tr>
<tr>
<td>Ernest Henry</td>
<td>Roofed</td>
<td>Gantry crane</td>
<td>Steel supported concrete sub floor</td>
</tr>
<tr>
<td>Cannington</td>
<td>External</td>
<td>Portal crane</td>
<td>Fabricated steel</td>
</tr>
<tr>
<td>Century</td>
<td>Roofed</td>
<td>Gantry crane</td>
<td>Fabricated steel</td>
</tr>
<tr>
<td>Phu Kham / Ausenco</td>
<td>External</td>
<td>Tower crane</td>
<td>Fabricated steel</td>
</tr>
<tr>
<td>Lumwana / Ausenco, Bateman</td>
<td>External</td>
<td>Mobile crane</td>
<td>“Mushrooms”</td>
</tr>
<tr>
<td>Cadia</td>
<td>Internal</td>
<td>Gantry crane</td>
<td>“Mushrooms”</td>
</tr>
<tr>
<td>Boddington</td>
<td>External</td>
<td>Mobile crane</td>
<td>“Mushrooms”</td>
</tr>
</tbody>
</table>

Construction approach

The approach to construction can significantly influence the design of the plant. For example, in colder climates the construction of the plant buildings takes on a much higher priority to that in Australia, Africa and Asia. In fact plant buildings are regularly not included in the design in these countries. The presence of a building, the crane strategy for the project and the layout of the plant are critical to the constructability and the subsequent maintenance programs.

Plants inside a building can be erected using an external crane through the roof or using the gantry crane or the building can even be put up afterwards. Use of the gantry crane for construction can increase the required crane capacity because larger lifts are often encountered during construction.

¹ Estimates only
than during future operations and maintenance activities, with flow on impact on the building structure and cost. In cold climates this approach is often necessary.

Constructability reviews should be completed for all projects, preferably early in the planning process. These need to consider interfaces between disciplines, cranage studies and erection sequences, site access and comprehensive safety evaluations.

**Operator and maintenance access**

Plant layouts for similar projects can vary widely because of all the issue discussed here. As mentioned previously, one of the major inputs is the site cranage philosophy and future maintenance and operating access requirements that flow on from this.

A plant layout must use space efficiently while maintaining allowances for adequate access to key areas for maintenance and operations. This can be a very subjective issue and often an area which is compromised by inexperienced engineers or overdesigned for due to owners team input and previous experiences.

The location of valves, instruments, pumps, high wear parts and other items requires review for access and maintainability. Large footprint outdoor plants make some of this easier but other more compressed layouts require the use of gantry or portal cranes. Operational considerations may include ease of ball charging, reagent loading, storage and handling, sampling systems design, location of control rooms and facilities etc.

**Operating and maintenance labour costs and skill level**

The owner’s operating and maintenance labour costs can have a significant impact on the design.

Labour costs in Australia range from US$80 000/y to US$200 000/y per person for even menial roles. This requires that plants are automated, simple to operate and simple to maintain.

In comparison, labour costs in Asia are currently US$5000/y per person or less leading to greater focus on labour oriented solutions to operating and maintenance issues than in Australia.

**Future expansion plans**

Allowing for future expansion of a plant can be beneficial over the life cycle of a project, but can add significantly to the capital cost of the project. The definition of the potential expansion needs to be factored into the design and cost of the project at feasibility study stage to ensure adequate funding is available for the potential impact on footprint and layout.

**Capital sensitivity**

Projects have varying levels of capital sensitivity. Junior mining companies with limited funding options are typically the most capital sensitive and put heavy emphasis on capital reduction rather than life of mine cost optimisation. This requires that the engineer’s approach is very focussed on “fit for purpose” and “fit to schedule” (typically with a limited time horizon, say 10 years) rather than life cycle optimisation.

**WHAT DRIVES CAPITAL COST?**
Cost contributors

The typical capital cost breakdown of a concentrator can be summarised as per the breakdown in Table 5 and illustrated in Figure 3. Surprisingly, the relative percentage cost for each area does not vary greatly from location to location. The cost of labour, equipment and bulk commodities is higher in Australia than Africa and Asia. However, the effects of changes in labour productivity, labour rates, equipment cost and bulk material cost tend to negate any significant changes in the relative cost contributions if equipment and bulk materials are sourced locally.

Some specialist components, such as ring motors and large mills (until recently), could only be sourced on the “international” market and this tended to skew the equipment cost component if large mills were involved.

Table 5 Breakdown of Typical Concentrator Capital Costs

<table>
<thead>
<tr>
<th>Commodity</th>
<th>% Total Plant Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment</td>
<td>24 – 35</td>
</tr>
<tr>
<td>Plate and steel</td>
<td>4 – 6</td>
</tr>
<tr>
<td>Labour</td>
<td>15 – 20</td>
</tr>
<tr>
<td>Other bulks</td>
<td>25 – 30</td>
</tr>
<tr>
<td>Other directs</td>
<td>5 – 10</td>
</tr>
<tr>
<td>EPCM</td>
<td>12 – 15</td>
</tr>
<tr>
<td>Other indirects</td>
<td>4 – 10</td>
</tr>
</tbody>
</table>

Figure 3: Typical split in project direct costs (excludes EPCM and other indirects)
Cost drivers
Based on the split in typical concentrator costs, the cost drivers fall into four categories:
- major equipment, typically 80% of the total equipment cost (40% of total direct costs, or 32% of total plant costs);
- bulk materials (platework, steel, cable, piping representing approximately 20% of total direct costs), and
- direct labour related (earthworks, civils and equipment installation, representing about 20% of direct costs, and
- EPCM related labour representing approximately 14 to 18% of total project costs).

Opportunities for cost reduction for a given project are then driven by:
- reducing contingency in sizing of equipment, with consequential increase in project risk;
- using cheaper equipment sources;
- confining the area of influence of the project as much as possible (minimising project footprint);
- reducing plant footprint, and
- fabricating and potentially modularising the plant with a focus on doing work in lower cost locations.

If capital cost is key to getting a project financed and into production the approach to engineering, procurement and project management will be very different to that used where a project is optimised based on life of project outcomes. The level of detail required to quantify life of project costs objectively is substantial and usually beyond the resources of junior mining companies. Plant design outcomes therefore often reflect the experience of the engineering team and the need to reduce capital costs at the expense of some life of project “nice to haves”.

Contracting strategy
In a competitive market, opting for a lump sum or fixed price approach can reduce margins and promote innovation. This outcome is less likely in a market were engineering, equipment, fabrication and construction resources are in demand as per the current market as the vendor has the opportunity to fully offset the risk in the price offered to the owner. The appropriate balance between fixed price, rates based and reimbursed contracts is often a function of the project schedule and the status of design deliverables at the time of award.

CONCLUSIONS

The design and layout of a concentrator is based on a number of factors. The ore characteristics and process design inputs are a function of geology and good metallurgical practices. Interpretation of the design inputs and criteria can lead to variations in process flowsheet that impact on design layout and plant capital cost.

The impacts on plant design and capital cost due to location, terrain, altitude and climate are substantial. For plants that are not constructed within buildings, the maintenance and construction approach can have a large impact on design, schedule and cost. For “open-air” plants, the use of mobile cranes, gantry or portal cranes and tower cranes for plant maintenance will impact on plant layout and footprint.
Experience from previous operations and projects plays an important role in equipment selection and layout. Assessing the value of design alternatives or potential changes to plant design can be heavily impacted by the qualitative and semi-quantitative inputs making definitive assessment of value over life of business an intuitive process. Similarly, assessing the value of new ideas and innovation can be difficult due to existing paradigms and the risks associated with the unknown.

REFERENCES

