

Article

A Systems Engineering Approach to Incorporate ESG Risks and Opportunities in Early-Stage Mine Design and Planning

Micah Nehring * and Peter Knights 

School of Mechanical and Mining Engineering, University of Queensland, Brisbane, QLD 4072, Australia; p.knights@uq.edu.au

* Correspondence: m.nehring@uq.edu.au

Abstract: This study examines how ESG risks and opportunities can be systematically identified, assessed, and incorporated into the early-stage design and planning of natural resources projects. The focus for this study will be on the mining activities required to source the resources for the global decarbonization effort. The need for a framework to incorporate ESG risks and opportunities into the strategic mine planning process was first identified in the de Beers Sustainability Valuation Approach. The Social Value Capital Decision Model advanced by BHP represents an advance on the de Beers model. This is the first example of a structured methodology for systematically considering stakeholder values and incorporating these into the capital decision framework. To test the applicability of a new approach to mine design by using Quality Function Deployment (QFD), a case study involving a copper mine located in South America was developed. This case study demonstrates how QFD can provide clear line-of-sight to connect design decisions with priority stakeholder concerns. The framework provides a communications tool for aligning the ESG design process across functional silos within complex organizations. The development of appropriate software tools could assist in managing the inherent complexity associated with integrating stakeholder value concerns into early stage design decisions.

Keywords: ESG; sustainable mine development; stakeholder engagement; mine planning; systems engineering; quality function deployment (QFD)



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1. Introduction

Environmental, Social, and Governance (ESG) concerns related to mining refer to the impact (whether negative, neutral, or positive) of mining projects on the environment, community, and ethical corporate governance. The foundation of ESG is attributed the “triple bottom line” accounting measures introduced by [1], and later formalized by the United Nations in the 2004 report “Who cares wins” [2]. This paper applies a new methodology for incorporating ESG considerations into the mine planning process by using a systems’ engineering approach known as Quality Function Deployment (QFD).

In recent years, several events have contributed to heightened public awareness of Environmental, Social, and Governance (ESG) risks related to mining projects. These include the Brumadinho tailings dam failure in Brazil, the destruction of the Jukken Gorge cave in Western Australia, and heightened concern around the sectors’ greenhouse gas emissions contributing to climate change. ESG risks present the minerals industry with considerable uncertainty. ESG concerns present as “wicked problems” in that they can be highly context specific, involve multiple sectors of the community (local, regional, state, national, and international), require multi-disciplinary collaboration to resolve, and often require a balance between short- and long-term risks. Furthermore, community consent, once given, can be an ambiguous concept, not necessarily in the form of a legal contract that investors will accept and can be withdrawn without much advance notice as a result of events beyond a mining company’s direct control.

ESG risks and opportunities occupy the forefront of the minds of senior executives in the mining industry. Every year, the major accounting and management consulting companies in Australia (Deloitte, PricewaterhouseCoopers (PwC), Ernst and Young (EY), and KPMG) conduct surveys of the top ten issues occupying the attention of senior mining executives. ESG concerns have routinely topped these lists in recent years. Deloitte's "tracking the trends" report [3] lists valuing natural capital, the circular economy, and decarbonization as its top three concerns. EY, in their 2022 mining and metals risk and opportunity report [4], states that "ESG still tops the agenda for mining and metals companies but geopolitical uncertainty, costs and supply chains also demand leaders' focus".

Mining projects are generally characterized by a series of expansion projects or phases, as outlined in Figure 1. As the operation progresses through each phase, the return on capital tends to diminish. Key factors that destroy Net Present Value (NPV) are CAPEX over-runs and delays. Delays in approvals and the permitting process are often related to ESG concerns. A recent IEA report [5] estimated the global average lead time from discovery to production for lithium, nickel, and copper mining projects to be 16.9 years (12.5 years for discovery, exploration, and feasibility, 1.8 years for construction and planning, and 2.6 years from construction to production). If the world is to achieve net zero carbon emissions by 2050, lead times for the development of critical minerals projects will need to be significantly accelerated.

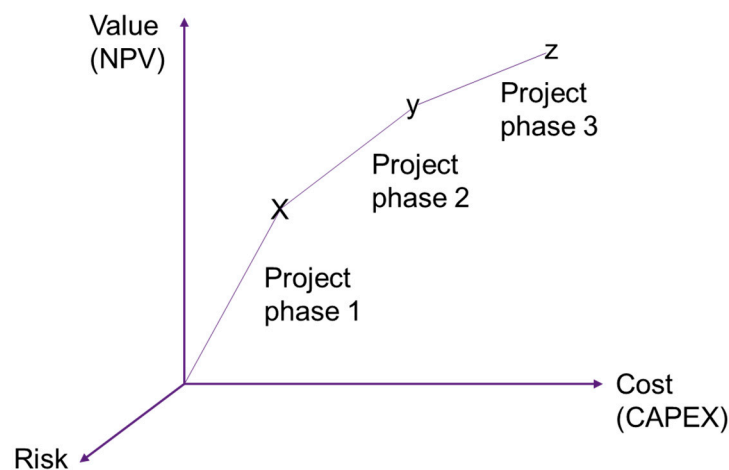
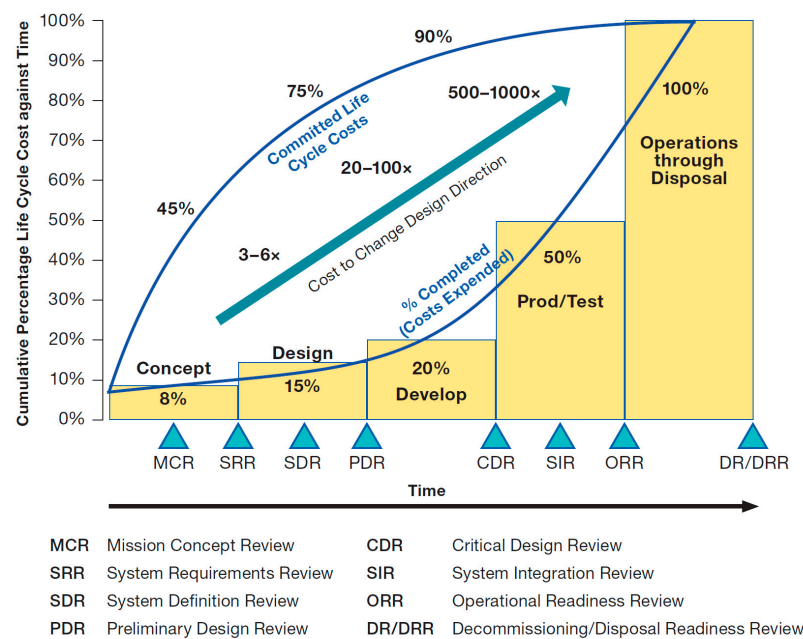


Figure 1. Mining proceeds as a series of expansion projects. Permitting and development delays destroy project NPV.

The mine planning process typically progresses as a series of studies involving concept, pre-feasibility (order of magnitude), feasibility, and, following Final Investment Decision (FID), detailed engineering, construction, operation, and phase-out. The first three stages can take many years and millions of dollars to undertake. Along with detailed Life-of-Mine planning outlining the extent and sequence of mine development, outputs at the feasibility stage include detailed environmental and social impact assessment studies (EIA and SIA, respectively). These are submitted to government authorities and various stakeholder groups for comment and permitting approval. It is not uncommon at this stage for stakeholder groups to contest this process, forcing companies to re-think major aspects of a project. This results in potential capital expenditure increase and project delays, both of which negatively affect project value for the mining company. Given that ESG issues are so prevalent in the delay of mineral resources projects, both at the outset as well as for each subsequent expansion, it is vital that ESG aspects are fully incorporated into the design and planning process as early as possible. This is not currently the standard industry practice.

Systems engineering is an interdisciplinary field of engineering and engineering management that focuses on how to design, integrate and manage complex systems over their life cycles [6]. Systems engineering uses modeling and simulation tools, use cases,

requirements analysis, and scheduling to manage complexity involving people, processes, and plants. Figure 2, from the NASA Systems Engineering Handbook [7], illustrates the life cycle stages for product design in the aerospace domain. In total, 75% of a product’s life cycle costs are “committed” in the early concept and design stages. By analogy, the majority of a mining project’s environmental and social risks (and costs) are “locked-in” in during the design stages of a mining project. ESG risks can be reduced and opportunities can be enhanced if they are designed for the mine plan as early as possible. However, sustainability departments within mining companies are largely populated by environmental and social scientists. These professionals work alongside mining engineers to elaborate Pre-feasibility and Feasibility studies of mining projects. This approach, however, risks the input of environmental and social scientists being viewed purely as “constraints” to the optimal mine design process. A truly integrative approach is required that elevates key ESG elements from constraint functions to design objectives.



Adapted from INCOSE-TP-2003-002-04, 2015

Figure 2. Product life cycle costs at each design stage [7].

The aim of this research is to demonstrate that a systems engineering framework derived from the Quality Functional Deployment (QFD) design approach can be usefully employed to systematically incorporate ESG aspects into the mine design and planning process.

This process is not intended as a substitute to the many specific management plans required to manage mining projects (water, air quality, energy and waste management, etc.). The framework essentially provides ‘line of sight’ for prioritizing and incorporating ESG risks and opportunities associated with mining and metals projects, elevating these from being considered as constraints to becoming explicit design objectives.

This study reviews the literature associated with the development of systems engineering, mine design and planning principles, ESG fundamentals related to mining, and social value frameworks employed by large mining companies. It then introduces QFD diagrams and discusses how these might be adapted to deal with stakeholder social value considerations and mine design and planning. Finally, a case study in which QFD is applied to a large open-pit copper mine in South America is presented to demonstrate the applicability and limitations of the systems approach.

2. Background

There is a large body of research in the open literature under the general theme of ESG within the mineral resources industry, some of which will be explored in further detail. However, few papers in the open literature specifically explore the incorporation of ESG into early-stage mine planning. We will thus firstly examine the few key literature items that do, and elaborate on their contributions and areas where further improvement may be warranted.

2.1. De Beers Sustainability Valuation Approach

The authors of [8] present one of the first studies which focus on the inherent opportunities as well as challenges in the effective integration of social performance issues into strategic long-term planning for mineral assets in South Africa. In doing so, the authors present the principles that define the Anglo American Social Way [9] framework for governing social performance. The model essentially consists of a four-step process:

1. Understand the project context. This includes identifying the key sustainability challenges and opportunities and identifying the key project decisions.
2. Generate options for key project decisions. This includes generating options for each key project decision and identify the sustainability risks and opportunities for each decision.
3. Analyze options and determine “value at stake”. This includes defining scenarios for each option, defining the assumptions to quantify the sustainability value at stake for each option, calculating the value at stake for each scenario, and calculating the NPV excluding and including the sustainability at stake for each option.
4. Recommend preferred options. This includes comparing the NPV of options and value at stake and recommending preferred options, defining the business case for preferred options, and recommending the preferred options to key decision makers.

2.2. BHP Social Value Approach

The authors have also reviewed the publicly available social value models and frameworks of many of the multinational operators, as well as engaging in productive discussions with industry experts in the area. While there may be differences in terminology between organizations, it is common for stakeholders to be grouped according to the environment, first nations, workforce, local communities, special interest groups, customers, suppliers, and shareholders. What shareholders ultimately want to understand is the trade-off between growth, returns, and risk and opportunity. A generalized version of a stakeholder ESG value decision model from BHP [10] is depicted in Figure 3.

As shown in Figure 3 [10], the first step involves gaining an understanding (discovery and characterization) of the social value opportunities and impacts across each stakeholder group, and identifying the key strategic value sources for each for a given project (the critical value scores should be highlighted). Step 2 then leads to a scenario analysis (multifactor evaluation) which compares projects or the development alternatives for a project. Each sub-element within each stakeholder group is typically rated and scored accordingly, resulting in an overall score for each stakeholder group. The third and final step (strategic alignment) involves deciding whether to pursue a project, and how that ultimately contributes to a company’s strategic social value objective, and the contribution that the project makes toward achieving that objective.

The authors of this paper propose that there exists a fundamental gap between the understanding (step 1—discovery and characterization) and analysis (step 2—multifactor evaluation) phase. This gap relates to a detailed scenario analysis of project alternatives relating to the key levers (process route, scale of operation, mining method, sequence and scheduling, and cut-off policy) for creating value as part of the strategic mine planning process. The important part of this is understanding and measuring/quantifying how the risks and opportunities at the project level change with a change in each lever. It is this level of granularity that is required at strategic mine planning to fully incorporate ESG risks and opportunities. This step will also identify Go/No-Go risks, risks that can be treated as a constraint, risks that can form part of an objective function, and will also have a Life-of-Mine (LoM) vs. tactical risk/value/opportunity trade-off.

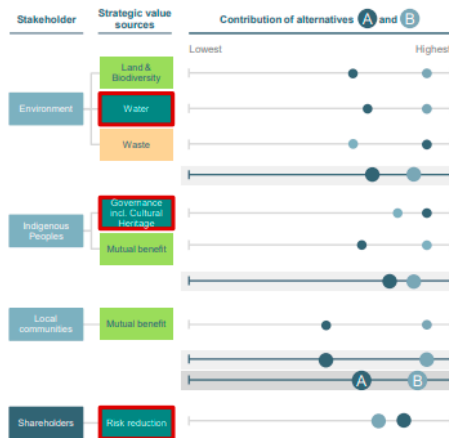
We are piloting social value decision evaluation tools

Understanding
social value opportunities and impacts



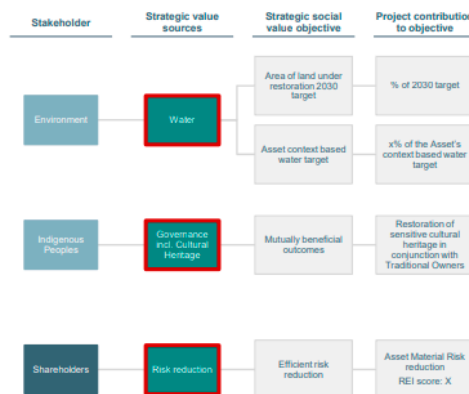
Analysing

all material sources of stakeholder value and determining the optimised investment alternative



Deciding

whether to invest using a consistent and transparent approach to evaluating contribution to strategic objectives



Social value decision evaluation and judgment

Figure 3. Social value capital decision model [10].

2.3. Codes of Practice, Policies, and Guidelines

According to surveys conducted annually by the big four accounting companies (Deloitte, PWC, EY, KPMG), over the last decade, Environmental, Social, and Governance concerns have climbed to become the number one concern amongst the executive managers of mining companies. Several voluntary codes of practice and guidelines have been developed to assist the diffusion of industry best practice. Many of these seek to incorporate fundamental aspects of the United Nations Sustainable Development Goals [11]. Principal amongst these are:

- The ICMM framework for environmental resilience, social performance and governance and transparency. ICMM is “a leadership organization working for a safe, just and sustainable world that is enabled by responsibly produced minerals and metals” [12].
- The Mining Association of Canada’s (MAC) Towards Sustainable Mining (TSM) initiative. The TSM protocol and frameworks provide measuring and reporting tools for ESG performance. Participation in the TSM initiative is mandatory for all MAC members for their Canadian operations [13].
- The European Partnership for Responsible Minerals. The EPRM is a “multi-stakeholder partnership with the objective to increase the proportion of responsibly produced minerals from conflict-affected and high-risk areas and to support socially responsible extraction of minerals that contributes to local development” [14].
- The Responsible Mining Foundation, an independent research organization based in Switzerland [15]. This organization only accepts funding from government and philanthropic sources, not from the extractive industry.
- Global Reporting Standards (GRI) [16] oversees the development of corporate sustainability and reporting standards. It provides a widely accepted means for certifying ESG measures. It is not specific to the extractives industry and has been operating for 25 years.

2.4. Other Literature

Changes to design processes to better incorporate sustainability/ESG because of a strong push from financiers, insurers, regulators, and customers have been making significant impacts in other industries for many years, including manufacturing [17,18], maritime [19] and food and beverage industries [20]. The resources industry is now rapidly moving in the same direction, with more attention being directed toward considering attributes of sustainability/ESG within the block modeling and mine planning process (early stage). Refs. [21–23] suggest a clear link between a firms’ sustainability practices and its performance. Ref. [24] advocates for an approach that balances the trade-off between NPV estimation and social and environmental impacts (positive and negative) to evaluate several project options to produce a more realistic business analysis. This section of the report reviews some of the practical initiatives that have been undertaken within the mining industry to incorporate ESG aspects into strategic mine planning. Much of this has been guided by some of the policy changes by various industry bodies, as detailed earlier.

Previous studies were found to address the effect of block sizes on waste generation [25]. Optimization studies to reduce diesel and arsenic emissions are presented by [26]. A focus on reducing acid mine drainage by [27] resulted in altered mine plans with noteworthy environmental benefits. Ref. [28] develops a holistic methodology based on a multi-criteria analysis; however, this was based on an assumption that many of the social factors were able to be measured and converted into value that could be efficiently used in the strategic mine planning process.

Ref. [29] propose a methodology that integrates four environmental and one social attribute into the ore resource evaluation and mine planning process. These include energy consumption, GHG emissions, water consumption, AMD generation, and direct employment generation. Two different sustainable cases were simulated and visually presented; these were the inclusion of all environmental attributes and man hours considered as costs, and the inclusion of all environmental attributes and man hours considered as benefits. The differences were clearly visible. The variables that were chosen were able to be measured in a relatively straightforward manner.

Ref. [30] undertook a rigorous Integrated Mine Planning Process (IMPP) for their underground coal mining operation to ensure that the mine plan submitted through the Subsidence Management Plan (SMP) application to the government has the highest probability of approval and will provide the most sustainable outcomes for the environment, community, and Illawarra Coal. Consideration of carbon price was considered by [31,32] in their strategic mine planning approach for an open pit metalliferous operation. Ref. [33] provide a comprehensive overview of social site characterization and the relevant works that had taken place up to that point. The authors propose a structure for social site characterization; however, once again, many of the outputs are intangible.

Research is required to quantify the impacts of ESG risk on the strategic framework. This is a complex area that is significantly impacted by the strategic decisions made for the development of any mineral asset, with [34–40] viewing ESG similar to other risks, and thus appear to account for it by developing a distribution of mine plans (and respective values) to reflect the highly variable nature of project risks. The use of utility curves has also been floated to account for risks. While this may take into consideration various project risks, the verdict is still out whether this approach can adequately account for the upside opportunity of incorporating ESG into early-stage mine planning.

2.5. Background Summary

While the above works are noteworthy attempts at providing structure to incorporating sustainability aspects into the block modeling and mine planning process, many are narrow in scope, applied late in the design process, contain a cross-correlation between variables that is not adequately considered, do not recognize the strategic versus tactical trade-off that inherently exists in considering these variables, are not able to influence major design decisions, and/or treat ESG predominantly as a risk, failing to see any upside opportunity.

While these deficiencies exist, it is also apparent that most of the 'E' variables are measurable/quantifiable (e.g., carbon intensity, water requirements, etc.), with many of these able to be input into the block modeling stage. The authors note the scarcity of scholarly works that adequately quantify the 'S' and 'G' variables. These tend to be qualitative parameters that cannot readily be measured or converted into 'a value' for inclusion into the block modeling process.

It is apparent that the issue that researchers and industry alike are grappling with is largely around the 'S' (Social) aspects. This is due to the intangible nature (inability to adequately measure) of these variables. They are therefore not readily able to be incorporated into the block modeling and mine planning process.

While the previously reviewed codes of practice, guidelines, and frameworks provide a high-level approach, they do not propose a structured methodology for incorporating decisions (key levers for value creation) related to the mine design and planning process at project level. That is what this paper proposes to address.

3. The Design Gap

Strategic mine planning is concerned with those decisions that largely determine the value of the mining business, whereas tactical or operational mine planning deals with the tasks required to achieve that value. Both types of planning are necessary, and while they can be addressed separately, they cannot/should not be separated in practice.

Strategic mine planning focuses on those technical variables that affect the life of a mine and the value of the underlying mineral resource. This starts with the discovery of the mineral resource, and finishes with mine closure and rehabilitation.

Figure 4 illustrates the strategic mine design process. This diagram is adapted from the Rio Tinto strategic mine design process, as described by [41]. The diagram depicts a linear sequence of steps; however, it should be noted that, in practice, the design process incorporates loops, as new information and optimization often requires that stages be selectively revisited.

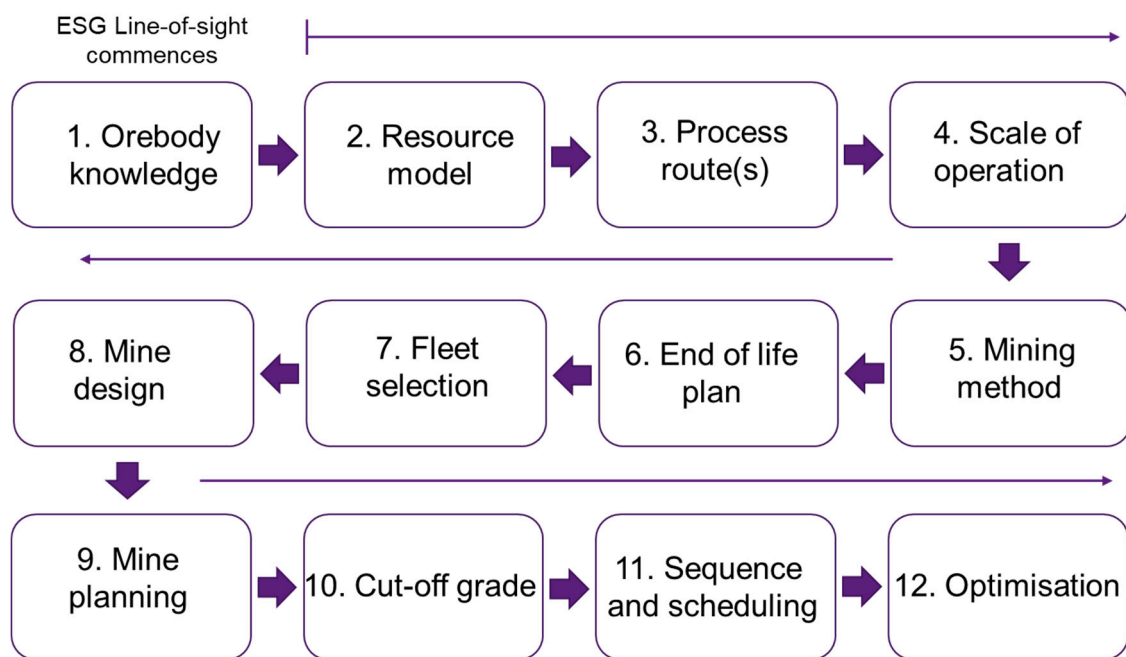


Figure 4. Strategic mine design process (Adapted from [41]).

The first step of the process (1. Orebody Knowledge) begins with capturing and modeling all information relative to the orebody. Knowledge concerning the geography, geological, geo-technological, geo-metallurgical, geo-environmental, and geo-metallurgical and hydrogeological features of the orebody must be understood, and the physical characteristics must be determined and mapped.

In the next step of the process (2. Resource Model), market variables (supply, demand, and price), legislation, and risk are considered to establish the resource model. The risk assessment necessitates conducting environmental and social impact assessments, as well as weighing up geo-political risks. In Australia, resource estimates must be compliant with the Joint Ore Reporting Code (JORC) developed by the Australasian Institute of Mining and Metallurgy. Once proven and probable reserves have been estimated, options for the mineralogical and metallurgical processing of ore need to be considered (3. Process routes). This might be a choice between flotation and leaching, for example.

Following selection of the appropriate process route(s), the mining method must be selected (5. Mining Method). This involves choosing between underground and surface mining methods. It will also involve choosing between bulk and selective mining methods, bulk in the case of massive deposits where grade is mostly invariable, and selective in the case of deposits where grade is highly variable and disseminated. At this point, the End-of-Life plan should be determined for the mine (6. End-of-Life plan). Will the mine be left as a void, or will it be backfilled or repurposed upon closure? These are some of the options for End-of-Life.

Fleet selection proceeds by selecting loading equipment appropriate to the type of mining (7. Fleet selection). Once loaders have been selected, materials transport options, including mining trucks, shaft, and conveyor haulage must also be considered and specified. Once overall power and labor requirements have been determined for the mined and process plan, mine design can begin in earnest (8. Mine design). This consists of determining access for roads, power and water supply, the ultimate pit (for a surface mine), limiting depth (for an underground mine), plus suitable geotechnically stable locations for tailings and waste dumps.

Mine planning consists of determining an appropriate sequence of development phases known as pushbacks for open-pit mines (9. Mine Planning). It also involves estimating the equipment and labor resources required for each phase. Within each phase, one or more cut-off

grades determine the destination of material, whether this be ore, marginal grade, or waste (10. Cut-off grade). To optimize the Net Present Value of a mining operation, a sequence of usually declining cut-off grades is applied to each phase. These are known as dynamic cut-off grades and are determined using an algorithm first developed by [42]. Application of dynamic cut-off grades determined the relative quantities of waste and ore to be mined from each phase. Commonly, two or more phases will be under development at any time during the life of the mine (11. Sequence and scheduling). This is because development must be sequenced to access ore in each phase so as to never interrupt the feed to the process plant. The plant represents the largest capital investment in the mine, and thus its production time should be optimized.

On the final step, optimization, decisions made in the previous process steps are reviewed and revised (12. Optimization). Sometimes, this is because new drill exploration information has enhanced the economically recoverable parts of the orebody. ESG line-of-sight commences with the resource model, and flows all the way through the design process.

The main decisions that mine planners have control over are [43]:

- Processing route;
- Scale of operation;
- Mining method selection;
- Sequencing and scheduling;
- Cut-off grade policy;
- End-of-Life pathways.

These key levers as part of the strategic mine planning process account for most of the value that can be attributed to most mining operations. In practice, according to traditional mine planning theory, all levers should be evaluated simultaneously to generate the optimal economic value. All levers are interrelated in the sense that they cannot be determined in isolation from each other. Moreover, they cannot be determined without considering the geography, geological, geo-tech, geo-metallurgical, geo-environmental, hydrogeological, geo-political, market, and social inputs/features.

The mine plan should be viewed as a working document, even in the production phase of an operation, to continuously map out the optimal path for exploitation of the deposit with the information that is available at the time. The mine plan may identify areas in the input models that are lacking, and require further study for later update and input back into the planning model. Even though enhancements to a mine plan may be possible once it has been implemented the opportunity to develop, a mineral deposit will generally only ever occur once. It is therefore vital that mine plans be generated with the greatest of care.

3.1. Stakeholder Value Drivers

BHP's social value model lists seven main stakeholders for mining operations [10]. The authors have added an eighth stakeholder, being Government. The full stakeholder list, and associated stakeholder values, that this project will move forward with include the following:

- Environment (GHG emissions; Biodiversity; Water use and access; Water quality; Air quality; Noise; Non-mineral waste and recycling; Tailings and mineral waste).
- Indigenous peoples (Culture and Indigenous heritage; Land access and resettlement; Meaningful participation; Mutual benefits).
- Workforce (Occupational health and wellbeing; Inclusion and diversity; Career development and training).
- Local communities (Livelihoods and mutual benefit; Community education; Community health and safety; Human rights and governance; Meaningful participation).
- Customers (Commercial license to operate; Security of supply; Product quality and consistency; Opportunity for growth; Product stewardship and trust; Circularity).
- Suppliers (Commercial license to operate; Supplier capacity building; Product stewardship and trust; Circularity).
- Government (Tax and royalty contribution; Regional employment opportunities; Regional development).
- Shareholders (Growth; Returns; Risk and opportunity).

Note that the Environment is recognized here as a stakeholder with similar rights as an individual. This trend is already evident in some legal systems, such as recent waterways legislation introduced in New Zealand. It is important to note that stakeholders and priorities may change from project to project.

3.2. How Do We Design for ESG Risks/Opportunities?

Having established the key stakeholder value drivers, the question becomes what stage of the mine design process can impacts best be mitigated or opportunities enhanced? All mine design begins with a characterization of the orebody. Based on the geo-metallurgical characteristics of the orebody, one or more feasible process routes will be feasible (e.g., leaching or concentrate routes). The chosen process route ‘locks in’ certain energy, water, biodiversity, tailings, and closure impacts, as depicted in Figure 5.

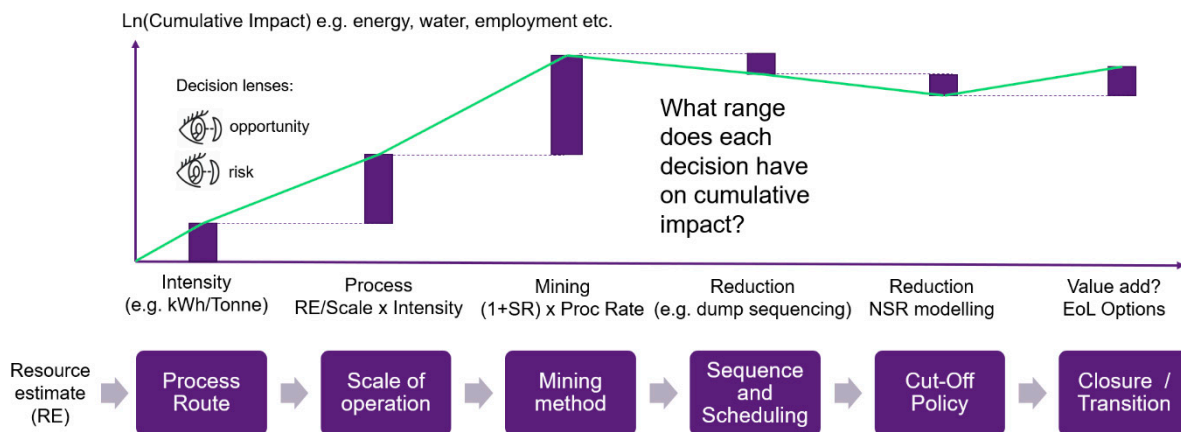


Figure 5. Cumulative impact of design decisions.

A key economic variable is the capacity of the process plant. Determining the scale of the process plant magnifies the impacts of processing. It also ‘locks in’ the amount of Run of Mine (RoM) material that must be mined each day, which in turn determines the amount of waste that must be removed (via the stripping rate), or, if an underground mine, the development rate required to access new ore supply.

At this stage, it is also important to appreciate the trade-offs that exist between dealing with stakeholder priorities at strategic planning versus tactical planning. As an example, we may design waste dumps and extraction sequences to manage dust at a strategic level. However, dust may also be managed at the tactical level through dust suppression measures (wetting haul roads). For this type of trade-off, a bow-tie analysis is recommended.

The process of mapping stakeholder priorities to design drivers highlights mine design options that represent go/no-go scenarios, constraints to the overall system, or whether the objective function needs to be revised.

3.3. Concept Development

Mine planners are ideally able to aid the decision-making process by mapping the change/range associated with stakeholder priorities along the six key value drivers. Figure 5 shows the cumulative (logarithmic) impact of mine design decisions. The first three steps (Process Route, Scale, and Mining method) determine total cumulative impacts. The latter two processes, Sequencing and Cut-Off Grade optimization, can reduce impacts through smart design. For example, smart scheduling can reduce vertical lift required for waste dumps, thus reducing diesel consumption. Cut-off sequencing can incorporate penalty costs for certain geo-metallurgical characteristics (e.g., hardness, silica content, etc.) which can be factored into a Net Smelter Return optimization, designating some material too expensive to process.

This helps to assess and understand the risk as well as opportunity associated with each design option.

3.4. Dependency Mapping

A mapping exercise was undertaken to understand which stakeholder priorities can be quantified and incorporated into the block model and which cannot. The process commenced with the identification of key stakeholders, in this case the eight key stakeholder groups highlighted previously. These eight key stakeholders were then identified as having thirty-one value drivers. The next step involved mapping the key levers as part of the strategic planning process against the 31 stakeholder values. The likelihood and impact of each design decision was evaluated against each of the 31 stakeholder value drivers on a Low (L), Medium-Low (ML), Medium (M), Medium-High (MH), and High (H) scale, as shown in Figure 6.

No.	Value Driver	Process Route				Scale				Mining method				LOM Schedule				COG Strategy				EOL Pathway			
		Likelihood	Impact	Quantifiable	Block Model	Likelihood	Impact	Quantifiable	Block Model	Likelihood	Impact	Quantifiable	Block Model	Likelihood	Impact	Quantifiable	Block Model	Likelihood	Impact	Quantifiable	Block Model	Likelihood	Impact	Quantifiable	Block Model
1	Climate change (GHG emissions)	H	H	Yes	Yes	H	H	Yes	Yes	H	H	Yes	Yes	H	M	Yes	Yes	H	M	Yes	Yes	H	M	Yes	No
2	Nature (biodiversity)	MH	H	Yes	Yes	MH	H	Yes	Yes	H	H	Yes	Yes	M	M	Yes	Yes	M	M	Yes	Yes	H	H	No	No
3	Water use & access	H	H	Yes	Yes	H	H	Yes	Yes	H	H	Yes	Yes	M	M	Yes	Yes	L	L	Yes	Yes	H	H	Yes	Yes
4	Water quality	M	H	Yes	Yes	M	H	Yes	Yes	H	H	Yes	Yes	M	M	Yes	Yes	L	L	Yes	Yes	H	H	Yes	Yes
5	Air Quality	M	M	Yes	No	M	M	Yes	No	M	M	No	No	M	M	No	No	L	L	No	No	M	M	No	No
6	Noise	H	MH	Yes	Yes	H	MH	Yes	Yes	H	MH	Yes	Yes	M	M	Yes	Yes	L	L	Yes	Yes	L	M	No	No
7	Non-mineral waste and recycling	M	L	Yes	Yes	M	L	Yes	Yes	M	L	Yes	Yes	L	L	Yes	Yes	L	L	Yes	Yes	M	M	Yes	Yes
8	Tailings & mineral waste	H	H	Yes	Yes	H	H	Yes	Yes	H	H	Yes	Yes	H	H	Yes	Yes	H	H	Yes	Yes	H	H	Yes	Yes
9	Culture (Indigenous + heritage)	ML	M	Yes	Yes	ML	M	Yes	Yes	ML	M	Yes	Yes	M	M	Yes	Yes	L	L	Yes	Yes	M	H	Yes	No
10	Land access	ML	M	Yes	Yes	ML	M	Yes	Yes	ML	M	Yes	Yes	M	M	Yes	Yes	L	L	Yes	Yes	M	M	No	No
11	Resettlement	ML	M	No	No	ML	M	No	No	ML	M	No	No	M	M	No	No	L	L	No	No	M	M	Yes	No
12	Occupational health and wellbeing	M	ML	Yes	No	M	ML	Yes	No	M	ML	Yes	No	ML	ML	Yes	No	L	L	Yes	No	NA	NA	NA	NA
13	Employee engagement & corporate culture (inclusion & diversity)	M	M	No	No	M	M	No	No	M	M	No	No	L	L	No	No	L	L	No	No	NA	NA	NA	NA
14	Career development & training	M	M	Yes	No	M	M	Yes	No	M	M	Yes	No	L	L	Yes	No	L	L	Yes	No	M	L	Yes	No
15	Human rights & governance	M	M	Yes	No	M	M	Yes	No	M	M	Yes	No	L	L	Yes	No	L	L	Yes	No	NA	NA	NA	NA
16	Meaningful, inclusive participation	H	H	No	No	H	H	No	No	H	H	No	No	M	M	No	No	L	L	No	No	H	H	Yes	No
17	Livelihoods (Mutual benefit)	M	M	Yes	No	M	M	Yes	No	M	M	Yes	No	L	L	Yes	No	L	L	Yes	No	M	MH	Yes	No
18	Community education	M	M	Yes	No	M	M	Yes	No	M	M	Yes	No	L	L	Yes	No	L	L	Yes	No	M	M	Yes	No
19	Community Health & Safety	MH	MH	Yes	No	MH	MH	Yes	No	MH	MH	Yes	No	M	M	Yes	No	L	L	Yes	No	M	MH	Yes	No
20	Commercial licence to operate	MH	H	Yes	No	MH	H	Yes	No	MH	H	Yes	No	M	M	Yes	No	L	L	Yes	No	M	M	Yes	NA
21	Security of supply, product quality and consistency	M	MH	Yes	No	M	MH	Yes	No	M	MH	Yes	No	M	M	Yes	No	M	M	Yes	No	NA	NA	NA	NA
22	Economic contribution suppliers (Opportunity for growth)	H	M	Yes	No	H	M	Yes	No	H	M	Yes	No	L	L	Yes	No	L	L	Yes	No	M	L	Yes	No
23	Product stewardship & trust (Brand & reputation)	M	MH	No	No	M	MH	No	No	M	MH	No	No	L	L	No	No	L	L	No	No	M	MH	Yes	No
24	Circularity	M	L	Yes	Yes	M	L	Yes	Yes	M	L	Yes	Yes	L	L	Yes	Yes	L	L	Yes	Yes	M	MH	Yes	Yes
25	Supplier capacity building	MH	M	Yes	No	MH	M	Yes	No	MH	M	Yes	No	M	M	Yes	No	L	L	Yes	No	M	MH	Yes	No
26	Growth	H	H	Yes	Yes	H	H	Yes	Yes	H	H	Yes	Yes	H	H	Yes	Yes	M	M	Yes	Yes	NA	NA	NA	NA
27	Returns	H	H	Yes	Yes	H	H	Yes	Yes	H	H	Yes	Yes	H	H	Yes	Yes	M	M	Yes	Yes	NA	NA	NA	NA
28	Risk & opportunity	H	H	Yes	No	H	H	Yes	No	H	H	Yes	No	M	M	Yes	No	M	M	Yes	No	M	M	Yes	No
29	Tax contribution (Taxes & royalties)	H	H	Yes	Yes	H	H	Yes	Yes	H	H	Yes	Yes	H	H	Yes	Yes	M	M	Yes	Yes	NA	NA	NA	NA
30	Regional employment opportunities	H	H	Yes	No	H	H	Yes	No	H	H	Yes	No	M	M	Yes	No	L	L	Yes	No	M	M	Yes	No
31	Regional development	H	H	Yes	No	H	H	Yes	No	H	H	Yes	No	M	M	Yes	No	L	L	Yes	No	M	M	Yes	No

Figure 6. Mapping of value drivers against levers for value creation.

As shown in Figure 6, Process Route, Scale, and Mining Method were identified as the most likely and most impactful (with a rating of M, ML, or H) across many of the 31 value drivers.

The fifth and sixth step in this mapping exercise required the identification of whether each of the value drivers could be quantified and whether each of the value drivers could be incorporated into the block model at each design decision, respectively. This resulted in three distinct groups of variables/parameters, as follows:

1. Those that are quantifiable and can be incorporated into the block model.
2. Those that are quantifiable, but cannot be incorporated into the block model.
3. Those that are not quantifiable and cannot be incorporated into the block model.

3.5. ESG Factors That Can Be Quantified and Incorporated into the Block Model

It is evident that most of the 'E' variables are amenable to being quantified and are able to be incorporated into the block model. The exception to this is 'air quality', which is quantifiable, but not readily able to be incorporated into the block model.

3.6. ESG Factors That Are Quantifiable but Not Readily Incorporated into the Block Model

The ESG factors that are quantifiable but not readily incorporated into the block model include the following:

- Air quality (E);
- Occupational health and wellbeing (S);
- Career development and training (S);
- Human rights and governance (G);

- Livelihoods (mutual benefit) (S);
- Community education (S);
- Community health and safety (S);
- Commercial license to operate (G);
- Security of supply, product quality, and consistency (G);
- Economic contribution for suppliers (S);
- Supplier capacity building (S);
- Risk and opportunity (G);
- Regional employment opportunities (S);
- Regional development (S).

This list contains a mix of 'S' and 'G' variables.

3.7. ESG Factors That Are Difficult to Quantify and Cannot Be Readily Incorporated into the Block Model

A unique selection of 'S' variables are not quantifiable and cannot be incorporated into the block model. These include the following:

- Resettlement (S);
- Employee engagement and corporate culture (S);
- Meaningful Inclusive participation (S);
- Product stewardship and trust (brand reputation) (S).

Not all ESG elements can be built into the block model. This particularly applies to the 'S' and 'G' variables. A transparent, logical, and trusted process is required to provide mine planners with a 'line of sight' to be able to assess risks and opportunities, and trade these off between various potential design options.

4. Proposed Solution: House of ESG

Quality function deployment (QFD) diagrams (Figure 7) are a systems' engineering tool first developed and applied in Japan in the 1970s for designing and manufacturing goods. Ref. [44] describes the use of QFD diagrams by Mitsubishi to build large ships. Use of QFD diagrams then rapidly spread into the Japanese automotive industry.

Using a simple matrix structure, customer needs (label 1 in Figure 7) are listed on the 'y' axis. These are translated (or "deployed") into design solutions on the 'x' axis (label 3). The priority of the customer's needs is listed in a column immediately succeeding the voice of the customer (label 2). The degree of fit of the solutions with the customer needs (label 4) is described in the center of the matrix using a simple numerical scale (e.g., 5 is a good fit, 3 is a medium fit, and 1 somewhat addresses a concern.).

On the right hand side of the matrix, an index can be calculated which assesses the degree of fit of the design in addressing individual customer concerns (label 9). A simple scale may show how well the current design configuration addresses customer quality needs relative to competitor products.

At the bottom of the matrix, a row beneath the matrix lists target values for the design solutions (label 5). For example, if "water efficient processing" is required, what is the target water consumption? Using a numerical scale, the technical difficulty of each design solution is assessed. This reflects the relative maturity of the technical solution being proposed. A weighted index can be calculated to determine the relative importance of each design solution in addressing the overall customer needs (label 6). This provides an indication as to the sensitivity of certain design solutions to the customer needs. An additional row lists the goal of each proposed design solution relative to the specified target value (label 7). These might be to design the target, or to maximize or minimize the design with respect to the specified target. In such a way, the design parameters are classified as either the constraint or objective functions as part of the overall design optimization.

The roof of the QFD diagram (label 8) represents a mapping of the trade-offs related to the design variables. A set of symbols is used to indicate negative or positive feedback between design variables.

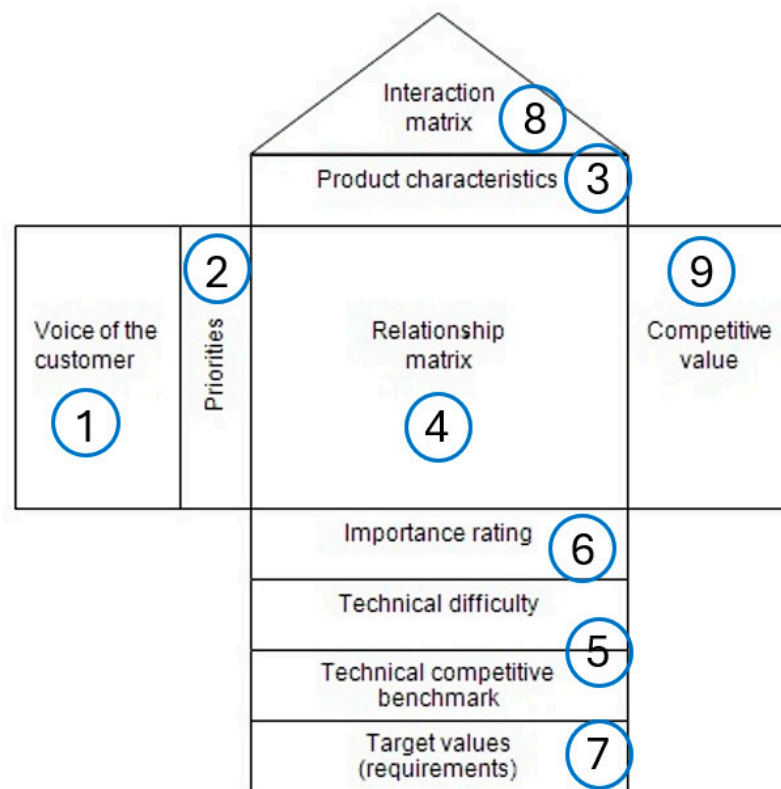


Figure 7. Quality function deployment: house of quality template (adapted from [45]).

For obvious reasons, QFD diagrams are often referred to as the “House of Quality” [46]. These principles can be applied to Mine Design by listing key stakeholder concerns in place of the customer needs. The mine design solutions should best address priority stakeholder concerns. In the Mine Design for the ESG framework, we have chosen to refer to the QFD matrix as the “House of ESG”.

4.1. Four-Phase House of ESG Model for Mine Design

The production of manufactured goods proceeds by: (i) listening to the voice-of-the-customer and translating these into customer needs; (ii) designing a product that meets these needs; (iii) determining the process by which the product can be manufactured; and lastly, (iv) devising an operational plan for producing the resultant product and bringing it to market. Ref. [45] are credited with devising a four-phase QFD model to represent these four design steps. The output of each phase becomes the input for the next phase (e.g., customer needs translated to design solutions, which in turn are translated into a process line that can then be operationalized).

We have chosen to represent the Mine Design for the ESG process as a four-phase Quality Functional Deployment (QFD) model, as depicted in Figure 8.

Phase 1 involves identifying the key groups of stakeholders involved in a proposed mining project and working with them to identify key values and concerns. Next, using the lenses of both risk and opportunity, concerns need to be prioritized. Some of these may involve go/no-go decisions related to resource development, and some may partially sterilize areas of the resource. These restrictions need to be reflected in the reserve model.

Phase 2 entails the development of conceptual design solutions whilst considering the priority stakeholder concerns. This phase will define the process and infrastructure design, the mining method, equipment, and scale of the mining project. It will also consider inbound and outbound logistics—how to get people, materials, energy, and consumables on site, and how to transport product and store tailings and other waste streams. The reserve model will be

affected by mine-design-modifying factors in this process, for example, decarbonized material transport options limiting the selection of the mining method and access to the orebody.

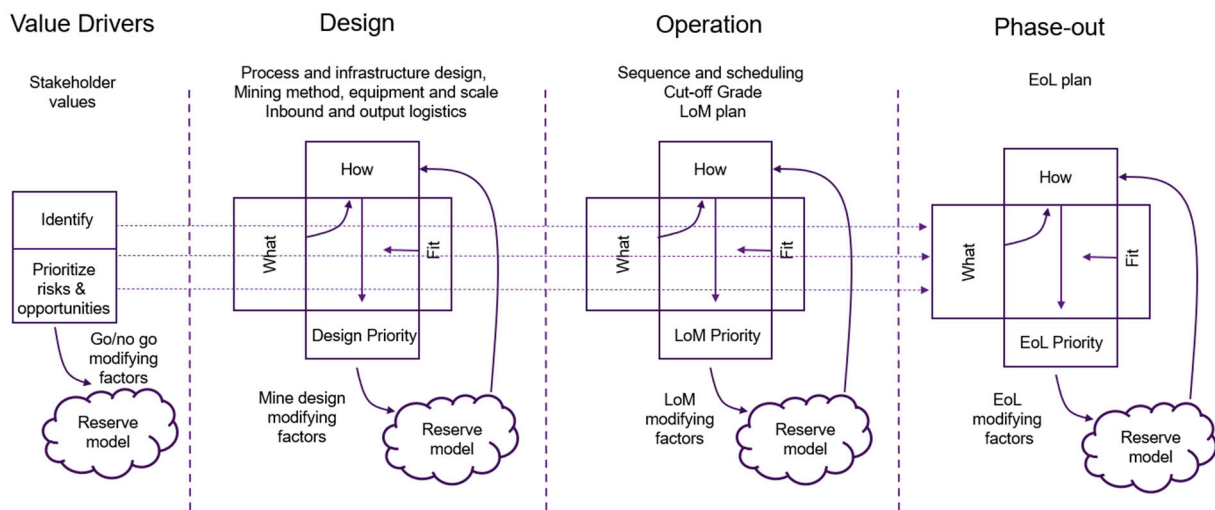


Figure 8. Four-phase Quality Functional Deployment (QFD) model (Adapted from [47]).

Phase 3 considers the operational phase of mine life. It examines cut-off grade strategy, sequencing, and scheduling over the Life-of-Mine. Certain mine design parameters determined in Phase 2 will be affected by Life-of-Mine (LoM) considerations, for example, the size and extent of pit shell expansions affecting haul roads and the ability to deploy trolley-assisting systems to decarbonize material transport. Once again, there is clear line-of-sight to the priority stakeholder concerns when making LoM decisions. A set of LoM-modifying factors will be applied to the reserve model.

Phase 4 considers End-of-Life (EoL) options for the mine. If the plan is to contour the waste dumps and convert the pit to water storage, then the mine design needs to accommodate these options from the start. The intended end use of a mine feeds back directly into the previous design and operation phases. Once again, a set of EoL-modifying factors will need to be applied to the reserve model.

The following sections use the QFD diagram to step the reader through the mine design process to identify key research questions related to incorporating ESG factors into early-stage mine design.

4.2. Key Stakeholders (QFD Label 1)

In assessing the viability of a mining project, it is essential to identify the key stakeholders affecting the project. The following questions must be asked:

- Who are the key stakeholders, and what are their values or concerns?
- What is their degree of interest in, and influence on, the project?
- What happens when stakeholder opinion is split?
- How can local, regional, and national concerns be balanced?
- What does meaningful, inclusive participation look like?
- How best to ensure adequate, ongoing consultation with stakeholder groups?
- How can mining companies best communicate complex design decisions to stakeholders?

“Trust” is at the heart of these issues. How can a mining company win “trusted partner” status? By necessity, this has to involve transparency and accountability, but how can CEOs develop a corporate culture that encourages these aspects? How does a company retain trust throughout the Life-of-Mine? What happens when public trust is lost?

4.3. What Are the Priority Concerns (QFD Label 2)?

Following identification of the key stakeholders, their ESG concerns must be identified and prioritized. For each of the ESG factors under investigation, this proceeds in two parts: discovery, and characterization. Discovery is the process of investigation and data collection. Characterization involves the analysis and classification of these data to generate information. This results in a “baseline” assessment for each ESG concern. Based on these assessments, an informed risk assessment can be undertaken to determine areas of major risk to a proposed mining project. The overall task is to identify priority concerns.

With respect to the discovery process, the following questions need to be asked:

- Can the project context for all stakeholder concerns be adequately documented?
- Can all stakeholder concerns be adequately measured (e.g., what are the measures of “meaningful engagement”)?
- How can social concerns be projected over the LoM?
- Are the data samples statistically significant?

With respect to the characterization process, the following questions should be answered:

- What threshold values have been applied to classify data (e.g., proven, probable, possible reserves)?
- How are data outliers best treated?
- How can data best be interpolated in “data voids”?
- How should “perception” best be monitored and managed in risk management processes?

4.4. What Design Solutions Address These Priority Concerns (QFD Label 3)?

The next stage in the QFD design process requires the determination of design solutions that best address priority stakeholder concerns. Key questions include the following:

- Have a wide range of conceptual solutions been adequately explored?
- How can novel solutions be effectively de-risked?
- How can potential technical solutions best be “stress tested” with stakeholders?
- Is there a “solutions library” to assist designers with technical solutions?
- In the face of changing legislation and public acceptance, will the technical solutions of today be acceptable tomorrow?

4.5. How Well Do These Solutions Address Priority Concerns (QFD Label 4)?

In this step, the adequacy of technical solutions is assessed against the priority stakeholder concerns. This involves developing models to assess the impact of design solutions.

Key questions that arise are as follows:

- How well do these solutions address priority concerns?
- How well do proposed technology solutions address stakeholder concerns?
- What is the trigger point to reevaluate design if stakeholder concerns change?

This area needs the development of models to evaluate impacts, particularly for “S” and “G” variables, e.g., Integrated mine planning/air quality modeling.

4.6. Constraint and/or Objective Functions (QFD Label 7)

In this stage, the design variables are assessed against the values assigned in the lower row of the matrix. Variables are classified as targets or constraints, or as part of the design objective function, which entails either a maximization or minimization objective.

4.7. Design Trade-Offs (QFD Label 8)

The roof of the QFD “house of quality” represents trade-offs that must be made during the design process. This requires evaluating how best to trade-off technical solutions in the following:

- Design/operations phases;
- Operations/End-of-Life phases;
- Design/End-of-Life.

The priority here is the need to develop stakeholder Net Impact metrics. This process needs to be transparent to stakeholder groups to maintain trust. A balance between simplicity and complexity has to be sought. One suggestion is to work with stakeholder groups to prioritize concerns, and then to identify and agree on a set of appropriate metrics, following which an Analytical Hierarchy Process (AHP) can be run to determine suitable weightings for the metrics.

Figure 9 illustrates how Net Impact metrics might be used to evaluate between two different mine design alternatives, labeled “Options A and B”. Option A provides superior financial return to Shareholders and Governments, but is slightly inferior with respect to the impact on the Environment and Indigenous peoples. It may be that Option B provides the project with a superior license-to-operate. The risk reduction associated with this option will need to be carefully weighed up against the financial penalty imposed on the project.

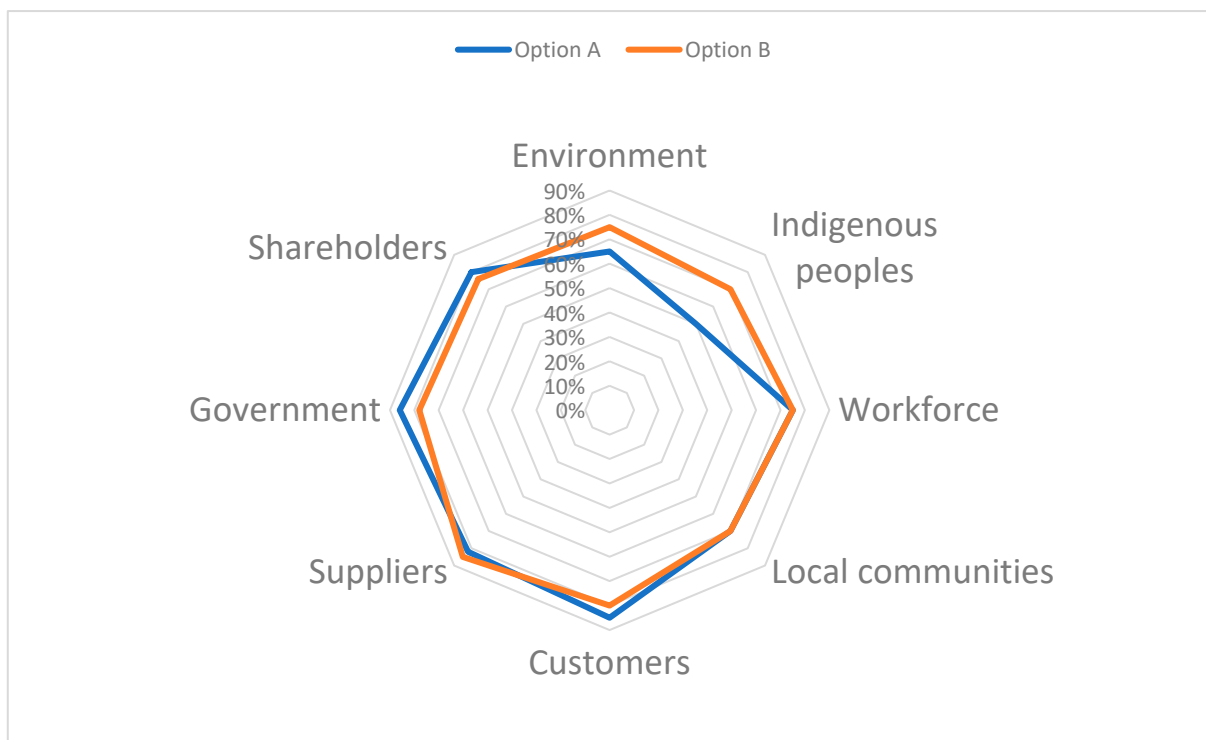


Figure 9. Evaluating Net Impact for stakeholder groups.

4.8. Adequacy of Design (QFD Label 9)

The column at the extreme right of the QFD diagram assesses the degree of fit of a particular design with the priority stakeholder concerns. It is a valuable means of communicating with stakeholders regarding the benefit/cost/risk of alternative designs.

Research projects deriving from this analysis include the following:

- Applying stakeholder Net Footprint Indicators (NFIs) to evaluate design trade-offs.
- Use of bow-tie analysis for evaluating design trade-offs.

4.9. Importance of Design Solutions (QFD Label 6)

The lower three rows of the QFD diagram are used to assess the feasibility and relative importance of the design solutions (Figure 7). A number is assigned to assess the technical and project risks associated with each proposed technology solution. A weighted impact variable can be calculated that assesses the relative importance of each solution. This helps determine project sensitivities. For example, novel solutions concerning tailing disposal could be expected to rate highly here.

5. Case Study

To test the applicability of the QFD approach to mine design, the authors worked closely with a large multinational mining firm to develop a case study of one of their copper mining operations located in South America. The case study necessitated close interaction with the firm’s Resource Development Group based out of their South American office. Due to the size and scale, the authors are unable to provide the QFD model that was generated for this in this paper; however, they are happy to provide some further detail of this if contacted. Figure 10 summarizes the technical inputs to the *x*-axis of the QFD diagram.

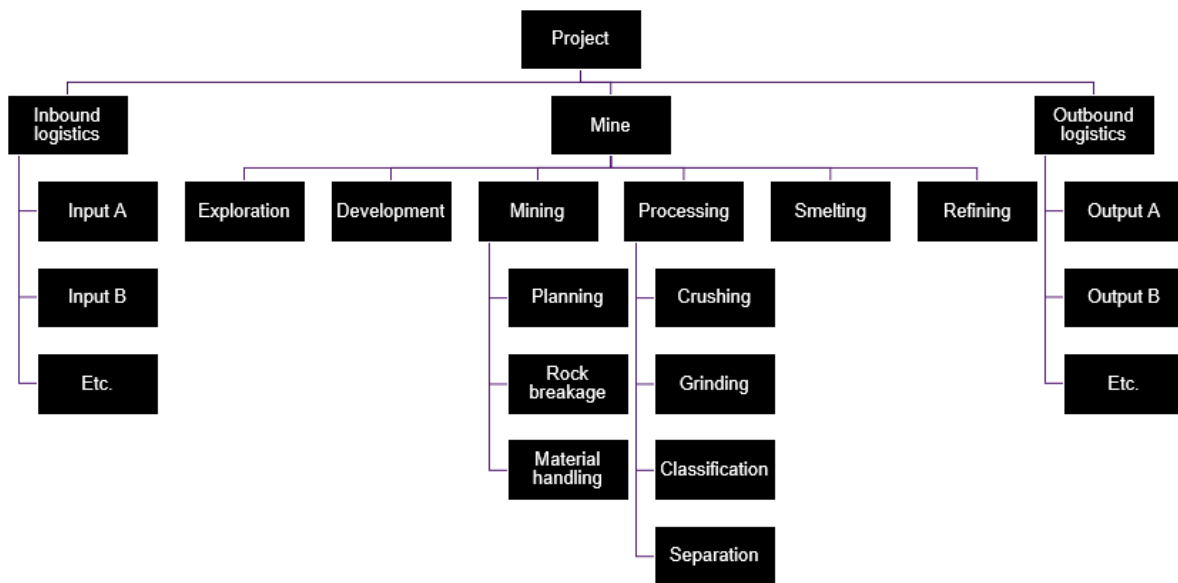


Figure 10. Technical inputs to the *x*-axis of the QFD diagram.

Figure 11 summarizes the stakeholder concerns on the *y*-axis of the QFD diagram.

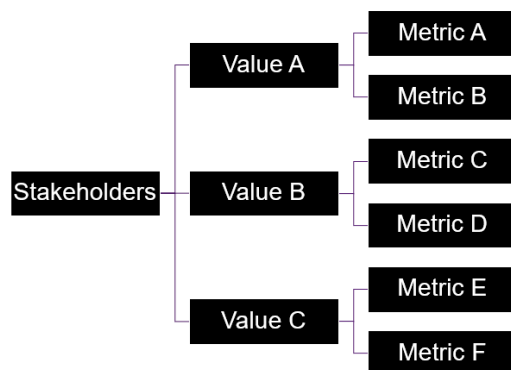


Figure 11. Stakeholder concerns on the *y*-axis of the QFD diagram.

The initial matrix involved 31 stakeholder concerns and around 40 independent technical decisions as part of the design. These technical decisions were ordered according to major mine processes. These include inbound logistics, exploration, development, mining, processing, smelting, refining, and outbound logistics. Inspiration for this classification comes from another systems engineering tool, namely SIPOC (Supplier, Input, Process, Output, and Customer) analysis.

The 31 × 40 matrix proved unwieldy to analyze, and so the South American team reduced the resolution of the QFD matrix by focusing on priority stakeholder concerns and key technical decisions. This reduced the complexity of the QFD diagram to around a 20 × 20 matrix. Some of the technical decisions being evaluated concern the following:

water supply (river vs. desalinated water), mining method (surface vs. underground), processing route (flotation, leaching, new technologies), and tailings storage (conventional slurry vs. hydraulic dewatered stacking). A unique aspect of the copper mining lease is that the mine must be backfilled at End-of-Life and the main water course re-routed to its original location. Ideally, this would entail a form of progressive remediation which will feed back into mine planning and sequencing decisions.

The copper mine case study demonstrates how a QFD diagram can provide clear line-of-sight to connect design decisions with priority stakeholder concerns. However, a limitation of the QFD approach is the complexity. Large product designers and manufacturers employ PLM (Product Lifecycle Management) software in place of QFD diagrams to better manage this complexity. Moving forward, the applicability of PLM software for managing mine design is an interesting avenue of research.

6. Conclusions

This article presents a framework (House of ESG) to provide a clear line-of-sight to connect design decisions with priority stakeholder values, and facilitates the trade-offs process of these values. In doing so, no-go constraints and those that must be minimized/maximized are clearly identified and valued. This framework provides a communications tool for aligning the ESG design process across functional silos within complex organizations.

The need for a framework to incorporate ESG concerns into the strategic mine planning process was first identified in the de Beers Sustainability Valuation Approach [8]. The Social Value Capital Decision Model advanced by BHP [10] represents an advance on the de Beers model. It is the first example of a structured methodology for systematically considering stakeholder values and incorporating these into the capital decision framework. Ref. [35] conducted a survey of mining-company–community conflict disputes that provides empirical evidence to assist in prioritizing stakeholder concerns.

Some 'S' and 'G' variables can be quantified, but cannot be readily incorporated into the resource block model. These include Occupational Health and Wellbeing, Development and Training, Human Rights, and Commercial License to Operate. A unique category of 'E' and 'G' variables are not quantifiable and cannot be incorporated into the block model. These include Meaningful Inclusive Participation, Employee Engagement, Corporate Culture, Product Stewardship, and Trust.

A four-phase Quality Functional Deployment (QFD) model was devised to manage ESG factors through the Life-of-Mine. This model provides for clear line-of-sight to priority stakeholder concerns when making LoM decisions.

- Phase 1 involves identifying the key groups of stakeholders involved in a proposed mining project, and working with them to identify key values and concerns.
- Phase 2 entails the development of conceptual design solutions whilst considering the priority stakeholder concerns.
- Phase 3 considers the operational phase of mine life. It examines the cut-off grade strategy, sequencing, and scheduling over the Life-of-Mine.
- Phase 4 considers End-of-Life (EoL) options for the mine.

To test the applicability of the QFD approach to mine design, a case study involving a copper mine located in South America was developed. The case study demonstrates how QFD can provide clear line-of-sight to connect design decisions with priority stakeholder concerns. The framework provides a communications tool for aligning the ESG design process across functional silos within complex organizations. However, a limitation of the QFD approach is the management of complexity. The development of appropriate software tools could assist in managing this complexity.

7. Future Research

It is apparent that future research is required to test and fine-tune elements of this approach. Those ESG aspects that are not easily quantifiable or able to be incorporated into

the block model should be prioritized for further investigation. Further research into this area can be classified into four categories, including:

- Measurements (including meaningful participation and characterization).
 - Framework for building trust and effective engagement in mining projects.
 - Developing stakeholder net impact measures.
 - Measurement and projection of social concerns over LoM.
 - Organizational alignment of Net Impact measurements (e.g., “at mine face” responsibility).
 - The role of perception to characterize risk.
 - “Concurrent permitting”: Working with government agencies for provisional permitting in early stage design.
 - Use of Product Lifecycle Management frameworks to manage critical infrastructure (e.g., tailing dams).
- Models (including impact assessment, adequacy, and sensitivity).
 - Investigation of ESG modifying factors in resource evaluation.
 - Valuing ESG risks using utility curves and other methods.
 - Apportioning risk in the block model and subsequent design of UPL and mine sequence.
 - Determining trigger points for re-evaluating project impact.
 - Integrated mine planning/air quality models.
 - Incorporating ESG risk into equipment life cycle models.
- Alignment (including concept generation).
 - “Co-design” of mines: How best to incorporate stakeholder opinion in the design process.
 - Application of stakeholder NFI indices to evaluate concept designs.
- Trade-offs (including constraints, targets, and optimization).
 - Stakeholder communication and negotiation strategies with respect to sensitive project variables.
 - Applying stakeholder NFIs to evaluate design trade-offs.
 - Use of bow-tie analysis for evaluating design trade-of.

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