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Ore-sand: A potential new solution to the mine tailings and global sand sustainability crises

FINAL REPORT

This report is dedicated to the families who have lost loved ones as a consequence of mine tailings storage facility failures worldwide, and the artisanal sand miners who work in circumstances of poverty and informality to mine the material that constructs our world.

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Final report

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Executive summary

After water, aggregates (sand, gravel, and crushed rock) are the second most exploited natural resource in the world. Their use has tripled over the last two decades to reach an estimated 50 billion tonnes per year, and the demand is growing exponentially around the world with urbanisation, development, population growth and sea-level rise. Yet, their extraction from rivers and the nearshore environment is already a global environmental and resource problem. Despite increased recognition of sand (and aggregates broadly) as a strategic resource for sustainable development, the issue remains largely unaddressed and unresolved in many places around the world. With infrastructure and construction a major feature of post-COVID recovery plans and aggregates the largest input demanded by this sector, the sustainability of aggregate production requires urgent global attention.

In 2019, the United Nations Environment Programme released the report 'Sand and Sustainability: Finding New Solutions for Environmental Governance of Global Sand Resources.' In the same year, United Nations Member States adopted the United Nations Environment Assembly (UNEA-4) Resolution of Mineral Resource Governance, which explicitly called for solutions to the challenges of global sand sustainability.

Awareness of sand sustainability is generating clear calls for alternatives at scale. Among secondary sources, one stands out globally – mineral ores. Currently large volumes of sand- and aggregate-like materials are produced by crushing mineral ores for the extraction of metals (and other commodities), which are then discarded as part of mine waste rock and tailings. Currently, it is estimated that 30 to 60 billion tonnes of mine waste are generated per year, making it the largest waste stream on the planet, an order of magnitude higher than all urban waste.

Attempts to give mining residues a second life have been made in the past, and suitability for certain applications has been proven. However, serious uptake has been impeded because: 1) these residues must be technically and economically competitive with conventional materials and 2) they were residues, rather than by-products that required their own optimisation to achieve specific properties during mineral processing. In this report we introduce the term ore-sand to signify this distinction and to differentiate sand produced as a by-product (or a co-product) of the processing of mineral ores.

After a series of catastrophic failures of mine tailings storage facilities in recent years that left severe environmental, social, economic, and human costs, the United Nations Environment Programme, International Council on Mining and Metals and the Principles for Responsible Investment introduced a new Global Industry Standard on Tailings Management. This and other recent reforms of mining, environmental and waste policy mean that large volumes of mine waste, in particular tailings, now need to be managed differently in many places in the world. The rising value of sand, the costs of storing mining residues, and the possibility of optimising mineral processing circuits for both primary commodities and ore-sand may give new impetus to a circular economy synergy with the potential for a strong contribution to sustainable development.

This 12-month project aimed to investigate whether by-products of mineral ores, with favourable mineralogical and physicochemical characteristics, can be a viable and sustainable source of substitute aggregate material for construction and other industries, and reduce the rising demand for sand extracted from the natural environment. Focusing on promising real-life examples, our research explores whether ore-sand from iron ore can provide a suitable, responsible and just alternative source of sand, and a solution to be considered as part of the UNEA-4 Resolution on Mineral Resource Governance.

In this report we share the findings of our analysis of an independently collected sample of ore-sand from one of Vale's largest iron ore processing sites in the state of Minas Gerais, Brazil. Since the devastating tailings facility failures that occurred at two iron ore mines owned or co-owned by Vale, the Córrego do Feijão and Germano mines, both in Minas Gerais, Brazil, Vale has accelerated its investment in the adoption of circular economy approaches to mine waste. In 2013, Vale initiated the Quartz Project to investigate whether sand by-products could drastically reduce the amount of tailings requiring storage at its mine sites, and a number of products are already undergoing market trials. These innovations are a significant shift for the mining industry and an innovation response that has the potential to address two global sustainability issues simultaneously: the safe management of mine tailings and the large and growing demand for sand. The potential is even more pronounced when we consider that the tailings storage facilities that present the highest safety risks to people (those located near where people live) offer the greatest opportunity of finding a market for ore-sand (because of the local demand for the material).

The recovery and supply of alternative aggregate materials, previously discarded as mine waste, can be viewed as a disruptive innovation that can challenge the existing norms and attitudes in the market. In this report, we also explore the sand market and different uses of sand; overview previous attempts of mine tailings (direct) reuse and its limitations; discuss the initial results from the life cycle assessment; develop an approach to mapping and matching mine tailings generation with sand consumption in different parts of the world; and present current results from interviewing major stakeholders in the aggregates market across several countries and regions. The results outline the broad landscape within which the relative advantages, compatibility, complexity, trialability and observability of alternative sands from mineral ores would have to be demonstrated and communicated. While relative economic and technical advantages seem to be the most critical factors, it is also vital to find a niche and pass regional and national regulatory gateways, work closely with customers and "allies" who would support demonstration of the material in use, and have a sound sustainability agenda including a holistic assessment of the environmental and social impacts and risks.

We need to use our sand resources wisely. We can reduce their use, recycle from construction and demolition waste, and substitute by other materials. Ore-sand is one of the possibilities but given the amount of such material (in the order of several billion tonnes per year), it is the option showing the largest potential to have a significant impact. If ore-sand can be used instead of sand taken from the natural environment, this will be a no regret option, as it would bring environmental, economic and societal benefits.

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Terms and definitions[1]

Development minerals are minerals and materials that are mined, processed, manufactured and used domestically in industries such as construction, manufacturing, infrastructure and agriculture (Franks 2020).

Aggregates is a term for granular material of natural, processed or recycled origin used essentially for construction purposes with an upper grain size limit of 75 mm. Segmenting into three aggregates subcategories is useful:

- **Primary aggregates** include rock, sand and gravels sourced from the natural environment. Crushed rock is extracted in hard rock quarries by blasting and crushing; and sand and gravels are extracted from pits by excavation, crushing, screening and washing (if required), dredged or pumped from lakes (lacustrine sand) and rivers (river sand), removed from coastal beaches, or dredged from the seabed (marine sand or marine aggregates).

- **Secondary or recycled aggregates** include crushed rock, sand and gravels produced by sorting, crushing and screening of construction and demolition waste materials.

- **Industrially-processed aggregates** – crushed rock and other sand and gravels substitutes produced through mechanical crushing of rock or an industrial process involving thermal or other modification.

Sand is a mineral granular material which does not stick together when wet and remoulded and where the combined weight of 50% of the particles is smaller than 4.75 mm. These materials are sourced from pits on land, hard rock which is mined and processed, from lakes, river beds and banks, wetlands, coastal beaches and nearshore waters. Additional qualifiers are needed for a precise and correct description of sand as a form of aggregates, for example a limit on the percentage of fines (material smaller than 75 µm) is often specified for concreting applications.

Gravel is a mineral granular material which does not stick together when wet and remoulded and where the combined weight of 50% of the particles is larger than 4.75 mm but smaller than 75 mm. These materials are sourced from pits on land, hard rock which is mined and processed, from lakes, river beds and banks, wetlands, coastal beaches and nearshore waters.

Manufactured sand (m-sand) is an artificially produced sand from a suitable source rock. The major production processes include crushing, screening and classifying to achieve the required properties for the use in concrete, asphalt, and other specific products.

Ore-sand (o-sand) is a type of processed sand sourced as a co-product or by-product of mineral ores. Typically, it is a result of mechanical crushing and grinding, different physical and physicochemical beneficiation processes for mineral concentrates recovery, including optimization of these processes and additional processing stages to achieve the required properties of sand.

[1] There are no universally accepted definitions for the terms sand, gravel and aggregates. The definitions in this report are based on the ISO 14688-1:2018, ASTM D2487:00, and 2020 UNEP/GRID-Geneva expert discussion 'What is sand?'. The term ore-sand is introduced in this report and defined by the present authors.

1 Global sand and mine tailings challenges

This section provides a brief overview of the global sustainability challenges associated with sand extraction and mine waste production, as well as recent international efforts to tackle both of these issues.

1.1 The global sand and sustainability challenge

Sand, gravel and crushed rock use has tripled over the last two decades to reach an estimated 50 billion tonnes per year, with demand still growing because of urbanization, population growth and infrastructure trends (UNEP, 2019). Sand, gravel and crushed rock are mined all over the world, accounting for the largest volume of solid material extracted globally (Peduzzi, 2014). Without them, there is no concrete, no asphalt, no glass to build the necessary schools, hospitals, roads, solar panels and other necessary infrastructure under current construction and industrial production systems and methods.

Sand is ubiquitous in construction and industrial production because it is cheap, versatile and easy to acquire. Yet, all indications are that we are approaching a future where access to this resource is a critical barrier to sustainability, and the full costs of uncontrolled sand extraction come due. Extraction rates of sand from dynamic natural systems are exceeding natural sand replenishment rates in many parts of the world (UNEP, 2019). There are growing concerns about shortages and scarcity of certain types of sand in different regions of the world (Sverdrup et al. 2017; Bendixen et al. 2019, 2021; Torres et al., 2017, 2021). Mounting scientific and anecdotal evidence across different countries and continents of over-extraction from dynamic river and coastal environments suggest geological and hydrological replenishment systems are no longer keeping up with human demands (Leal Filho et al., 2021).

Sand resources have been considered "a matter of national security" in some cases (Comaroff, 2014); but more often it fits the description of a Development Mineral (Franks et al., 2016; IRP, 2020; Franks, 2020): vital to economies and societies, but invisible in many ways. A call for improved sustainability in sand consumption and production practices is growing, however. In its resolution on **Mineral Resource Governance (UNEP/EA.4/L.19),** the 4th United Nations Environment Assembly asked all stakeholders to identify knowledge gaps and options relating to sustainable management of metal and mineral resources – including sand resources. A second UNEA-4 resolution on **Sustainable Infrastructure (UNEP/EA.4/L.5)** recognises infrastructure's centrality to the 2030 Agenda and requests the UN Environment Programme to collect best practices and identify existing knowledge gaps.

These two resolutions intersect when it comes to the issue of sand, gravel and crushed rock. Together, they encourage governments, businesses, non-governmental organizations, academia and international institutions, within their different areas of competence, to pursue our Sustainable Development Goals by promoting:

- Awareness of how sand extractive practices can have negative impacts on the environment when these activities are not properly managed, especially when they take place in dynamic environments like rivers, deltas, beaches and coastal waters.
- Due diligence and best practices along natural sand and gravel supply chains, addressing broad-based environmental, human-rights-, labour- and conflict-related

risks in extractive practices, including the continuing increase in transparency and the fight against corruption, with the support of the extractive Industries and infrastructure developers.

- Transparency initiatives, implementation and monitoring of existing social and environmental standards, and accountability.
- Public-private partnerships for sustainable management of metal and mineral resources – particularly within Sustainable Infrastructure initiatives.
- Research & development for technological, social, business and policy innovation to sustainably manage sand resources in the transition to green and circular economies.

If the UN sustainable development goals are to be met, efforts will need to move towards responsible sand sourcing that includes new alternatives to sand with comparable technical performance. Sand cannot be produced from our terrestrial, river and marine environments alone without irreversible environmental impact if we are to meet the increasing demand from a world preparing for 10 billion people. Where construction or traditional concrete cannot be avoided, reduction of natural sand use can be achieved through some tried and tested—as well as new emerging—technologies and materials. Reusing and recycling aggregates, either directly or from construction and demolition waste streams, is a long-established option where countries have mature built environments. Substitution with alternatives like by-products from other production and consumption processes (i.e. steel slag, fly and bottom ash from waste incineration, marble dust, waste foundry sand) is also common. Experimentation has led to a wide variety of green cements and concretes such as ultrahigh performance concrete, geopolymer concrete, lightweight concrete and limestone calcined clay cement (LC3). However, at current consumption rates, total sand avoidance is not possible and available alternatives cannot yet substitute a significant share of the global aggregates demand (UNEP, 2019).

The recently released final report on the implementation of the UNEA-4 resolution on Mineral Resource Governance, 'Mineral Resource Governance and the Global Goals: An agenda for international collaboration', called for "research on innovations in tailings management, reduction, recycling and re-use, in particular *the potential to re-use benign tailings material as an alternative to natural aggregate in the construction and land reclamation sectors*" (emphasis added). This report responds to this call.

1.2 Mineral ores as an alternative source of sand

For most mined commodities (with the exception of construction materials and some industrial minerals), the valuable minerals or metals of interest represent only a small portion in the overall mined volumes. Thus, the global mining industry generates billions of tonnes of waste every year. Due to the relatively low value of potential by-products from mine waste, remote location of most mines, as well as conventional waste management practices and environmental regulation allowing for massive waste storage, most mine waste currently ends up in waste storage facilities, such as waste rock dumps and tailings dams. In fact, mine waste is the largest waste stream on the planet, estimated to be in the range of 30 to 60 Bt per year (Lottermoser, 2010; Mudd & Boger, 2013), an order of magnitude higher than all urban waste (i.e. 2-3 Bt per year; Kaza et al., 2018).

The two major types of mine waste are waste rock and tailings. Waste rock typically comes from removing either uneconomic or barren rock in order to access the economic ore in the deposit (for a particular mineral). It is made up of a very coarse rock mass, stored in the waste rock dumps, sometimes also segregated based on its size, mineralogical and environmental properties (e.g. benign versus potentially acid-generating). In contrast, tailings originate from the processing of economic ores. They are the result of ore crushing and grinding, and are left over from mineral beneficiation processes, such as gravity-based separation, magnetic separation, and flotation, which are widely used for the recovery of valuable minerals. Consequently, tailings are mainly represented by fine and/or very fine material (sand, silt and clay size particles). Due to the fine nature, tailings typically have to be stored in specially engineered facilities such as tailings dams, requiring maintenance and regular monitoring of their physical and geochemical stability, as well as special measures for rehabilitation and closure at the end of operations. Franks et al. (2021) reported on the most comprehensive database of tailings storage facilities assembled, estimating that at least 8,100 (active, inactive and closed) facilities are present in the landscape, with 10 billion cubic meters (m^3; ~13 Bt) of additional tailings per year requiring storage in existing or planned facilities over the coming five-year period.

The amount and types of generated mine waste can vary drastically, depending on the type and size of the ore deposit, mineralization, mining and processing methods, and may also be affected by water and waste management practices, which are influenced by geographical location, climate, environmental regulation, technical expertise and social licence to operate. The opportunities for mine waste minimization, reuse, and repurposing have been investigated for a long time. However, these investigations have not resulted in any serious global uptake due to both technical and economic barriers. At the same time, significant efforts are often required to mitigate environmental impacts from mine waste storage facilities, e.g. acid and metalliferous mine drainage and dust emissions, ensuring their physical stability, rehabilitation and return to natural environment and/or finding another alternative land use at the end of mine life.

Whether mine waste is characterised as a hazardous or non-hazardous material, there may be opportunities for reuse and recycling that can provide sustainable alternatives to conventional waste management. This would allow additional valuable by-products (with potential substitution of other natural resources) to be recovered, as well as minimizing or avoiding massive waste storage facilities, which are often associated with the risks of geochemical and physical (in)stability over time and have been the cause of some of the most severe environmental disasters of humankind (Franks et al., 2011, 2021).

Some well-known options for the reuse of mine waste include feedstock for cement, bricks, tiles, and ceramics; aggregates for concrete, roads and other construction related applications; agricultural use such as soil amendments, pH control, and fertilisers; and feedstock for the chemical industry, e.g. pigments, and sulphuric acid production (Lottermoser, 2011). At the mine site, the reuse of mine waste can also include backfill materials for open voids and underground mines; aggregates for roads, landscaping, and embankments (e.g. for waste repositories); capping, cover (fill) and engineered soil materials for waste repositories rehabilitation and revegetation.

There has been no global reporting and no detailed estimates on the actual amount of mine waste being beneficially reused. The general assumption is a few per cent at best, with the majority of mine waste still destined for disposal. One explanation for the slow rate of uptake is that for the most part, reuse has focussed on mining residues, rather than producing by-products that require their own optimisation during mineral processing. This is a crucial distinction because mineral residues may not be fully optimised for the intended reuse purpose and can contain environmentally harmful minerals, elements and compounds (such as sulphides and metals), which unless separated from the product, can be a cause for concern. In this report we introduce the term *ore-sand* to signify this distinction and to differentiate sand produced as a by-product of the processing of mineral ores from the reuse of mineral residues. **An ore-sand refers to a type of processed sand sourced as a co-product or by-product[2] of the crushing and beneficiation of mineral ores**.

A second explanation is attributed to the disproportion between the total amount of waste generated versus amount needed in potential applications. While far more of the former is generated than there is a need for the latter, there is one potential exception – the reuse as a construction aggregate. The comparison of mine waste (~30-60 Bt/year) with the demand for construction aggregates (~50 Bt/year) shows that they are on the same scale. The generation of finer waste materials such as mine tailings (~10-15 Bt/year) also closely matches existing estimates for the extraction of sand from dynamic natural environments (~10 Bt/year). Although not all mineral ores can meet the requirements for sand as an aggregate material or are located close to markets, it is clear that there might be great opportunities for the production of ore-sands, contributing to a circular economy, both at the local and global level.

1.3 Are there opportunities for a circular economy transition?

The latest advancements in mining and processing technologies, combined with regulatory changes, growing global environmental awareness and expectations, and need for a transition to a circular economy, may assist in changing current approaches and practices in mine waste management, essentially leading to the possibility of "eliminating waste". The recovery of different by-products, progressive or con-current rehabilitation, stockpiling of pre-concentrated residual materials containing remaining valuable minerals for potential future recovery and reuse, as well as considering options and planning for alternative (economic) reuse of the land and some mining infrastructure at the end of mine life – are some key examples. For almost all materials that are mined and processed, there may be a beneficial application, which would result in generating additional economic, environmental, and/or social value (Golev et al., 2016). "Handling and processing mined materials in a way of and/or until reaching zero liability" could become a new disruptive business model in the resources sector aligned with the circular economy.

[2] The traditional distinction between terms co-product and by-product is strictly a function of mineral economics related to the revenue and/or profit from a given mining operation. A situation when a collective extraction of several minerals is required for a feasible operation represents the case of co-products. In contrast, by-products are rather incidental products that may or may not be recovered. With an increased recognition of environmental impacts and expected transition towards zero waste management, including affecting the permitting for mining in the first place, potential by-products from mine residues are in some cases becoming co-products. This highlights their equal importance in the design of mining operations and for the assessment of company's sustainability performance. In this report, we use both terms interchangeably, although by-product is the preferred term for known case-studies, while co-product refers to the (full) potential of alternative sand from mineral ores.

2 Circular economy transitions with alternative sands

The recovery and supply of alternative aggregate materials, previously discarded as mine waste, can be viewed as a disruptive innovation that can challenge the existing norms and attitudes in the market. In this section we explore the issues of innovation adoption and potential strategies for market penetration in relation to alternative sands.

2.1 What is the innovation?

Given that many alternatives already exist to sand extracted from natural environment, we frame the uptake of alternatives to sand at scale as an **innovation adoption challenge** in the transition to green and circular economies that enable economic prosperity based on ecological integrity and social equity (Kirchherr et al., 2017). Socio-technical transitions towards green and circular economies involve interlinked processes to create systemic shifts in production, consumption and waste management practices. *Niche innovations* in products, technologies, ideas, practices, regulations and policies emerge in localized settings. Successful innovations reform the relevant *regimes* of rules and institutions, which in turn can influence the wider *landscape* (the patterns shaping the interactions between social and natural systems and how they evolve) and transition from one state to another (Scoones et al., 2020). The notion of a 'just transition' extends to include the consideration of both broader inclusion in decision making around transitions, the distribution of costs and benefits of making these happen across different scales of geography, social groups etc., as well as the politics and power dynamics involved (Swilling, 2020).

There are at least three dimensions of niche innovation important to consider in the uptake of alternative sands:

- ➔ The **technical innovation** of a new aggregate material. Ore-sands are a new input material that comes from an unconventional source for the aggregates market. While there is currently no perfect solution to substituting sand in concrete, this material offers some potential worth exploring.
- ➔ Producing and using this material potentially require some degree of **process innovation** within mining companies, especially with regard to comminution (crushing), beneficiation (upgrading) and tailings management, and within use sectors, depending on the application for which naturally-sourced sand is being displaced.
- ➔ Diffusing technical and process innovations for ore-sand will require changes in policy, legislation, sourcing and use practices, and a transformation of the operating environment for aggregates sourcing and use, led by government, private sector and civil society actors. This is **institutional innovation**, defined by Raffaelli and Glynn (2015) in organisational and sectoral change applications as: "novel, useful and legitimate change that disrupts, to varying degrees, the cognitive, normative, or regulative mainstays of an organizational field".

2.2 Who are the innovation adopters to focus on?

The classic framework of Everett Rogers (Rogers, 2010) theorises the process of innovation diffusion and categorises types of adopters, while the work of Geoffrey Moore (1999) explores behaviours that characterise the process of adoption. The concept of 'Crossing the Chasm' is a critical idea in innovation theory that is highly relevant to the question of adoption of alternative sands innovation. Moore (1999) identified that the motivations and behaviours of innovators and early adopters and early majority and late majority adopters are fundamentally different: the adoption curve is discontinuous, with cracks between the different groups, recognizing that strategies for encouraging adoption in each of them must be different. Considering different categories of adopters allows for different needs, change and risk appetites, and incentives and barriers to change to be considered for different segments of the aggregates market.

Applying these insights, the primary user categories in the innovation adoption curve for ore-sands are:

- ➔ **Innovators:** Forward-looking individuals, teams and organizations inventing, experimenting with producing and/or using alternative aggregates, often motivated by technology-based problem-solving in local contexts, or specific applications. These may include materials innovation teams within larger companies, research entrepreneurs in university settings or inventive individuals in local settings.
- ➔ **Early adopters:** The early movers in mainstream aggregates markets, i.e. large scale aggregates producers and traders, infrastructure project commissioners and construction companies who watch outcomes from early adopters and are motivated by pragmatic considerations of economics, product price, quality and security of supply and infrastructure of supporting services.
- ➔ **Early majority:** The early movers in mainstream aggregates markets, i.e. large scale aggregates producers and traders, infrastructure project commissioners and construction companies who watch outcomes from early adopters and are motivated by pragmatic considerations of economics, product price, quality and security of supply and infrastructure of supporting services.
- ➔ **Late majority:** The mainstream aggregates market who are skeptical of change until the new technology has been proven to work. They are strongly influenced by market competition considerations: they are market leaders who are motivated to change sourcing, operations etc. only to maintain their position.
- ➔ **Laggards:** Traditionalists who lag behind the mainstream aggregates market who will only adopt new aggregates materials, sourcing practices or construction practices when there is no other viable option.

While still keeping an open mind, we have assumed that the adopters of alternative sands are mainstream organisations within the aggregates market – **or the early and late majority categories of innovation adopters.** Alternatives to sand exist in niche innovations like green concretes (e.g. review - Liew et al., 2017), reclaimed or recycled aggregates (e.g. reclaimed asphalt – Shi et al., 2018; scrap plastics – Aneke & Shabangu, 2021), other industrial by-products (e.g. waste foundry sand – Bhardwaj & Kumar, 2017) that address local aggregates supply or waste management challenges. The issue is not a missing innovation in technical materials but the movement of these materials into the mainstream aggregates market at volumes that can be considered a scaled solution to the sand and sustainability challenge. Such innovation is being impeded by the interconnected challenges of poor availability of large volumes of materials that can displace sand and gravel use in construction (aggregates) and a lack of demand for such materials from the mainstream aggregates market. In short, there is currently no perfect substitute for naturally-sourced sand and gravel in the major applications in which they are used in the construction sector, i.e. concrete production, backfilling.

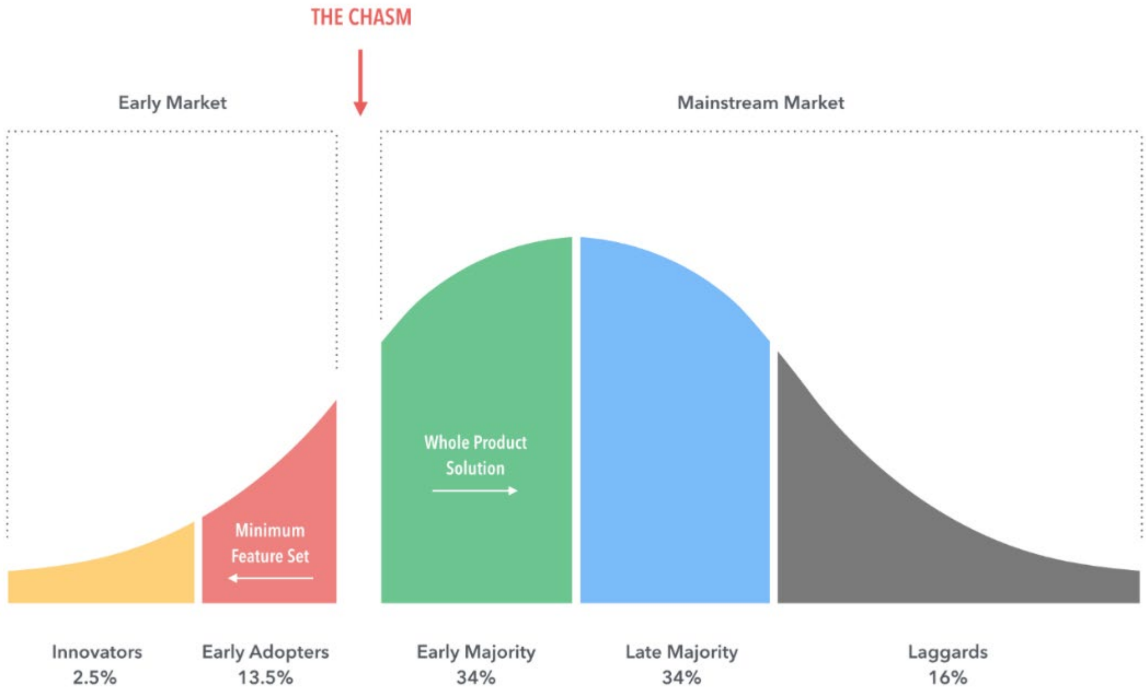

FIGURE 1. CROSSING 'THE CHASM' IN INNOVATION ADOPTION.

Image source: https://shahmm.medium.com/design-for-crossing-the-chasm-1c4d4c68a3f1.

2.3 Crossing 'the Chasm' for ore-sands

The Chasm in the adoption curve for ore-sands is the gap between values, preferences, incentives and constraints for innovators and early adopters on one side, and the early majority and late majority on the other. How each category considers what is "novel, useful and legitimate" (Raffaelli & Glynn, 2015) varies in function of the incentives and constraints for early and late majority and that needs consideration.

Making a just transition (Section 8) across the Chasm to circular economy solutions for sand consumption and production challenges will involve addressing core questions of technical performance, economics, security of supply and plural values and interests, and changing formal and informal rules that are operating in the real world to determine the mainstream market options for aggregates. Understanding the circular economy solutions to the sand sustainability challenges, that are perhaps present in mine tailings, entails understanding the challenges to overcome and the incentives for changes in behaviour by key end-users of sand extracted from rivers – the desired early and late majority adopters.

We use existing frameworks in innovation adoption studies (Kapoor et al., 2014; Polhill et al., 2019) to frame a set of interrelated hypotheses on what will influence adoption of ore-sands in accordance with the pragmatic motivations of the early and late majority to be explored in this analysis:

- ➔ Relative advantages**: the degree to which ore-sands are considered better than the preceding product, technology, concept or approach by key stakeholders in the context of market conditions.** Uptake of ore-sand as an alternative to sand and gravel taken from rivers, coastlines and the nearshore environment by the early majority is likely to depend on the alternative materials being technically and economically competitive with these conventional construction materials, as it has been shown by other recent explorations of tailings resource potential (e.g. Seal & Piatak, 2017). Economic factors for innovation adoption are likely to include traditional internal drivers (profitability, lower costs) and external factors (competitor behaviour, market drivers; Kempkens, 2015). Sustainability agendas and net contributions to the 2030 Agenda is a live issue for the mineral resource governance world, and as a result affecting the construction sector and the production, trade and use of aggregates. Sustainability opportunities and constraints are increasingly important as policy and citizen-driven changes affect the economics of production and consumption of mineral resources (Northey et al., 2018) as well as the 'Sustainable Development License to Operate' (IRP, 2020). As these trends continue to expand into the exploration, development and utilization of sand resources, we expect that early and late majority adopters will also want to know whether or not they *can and should* pursue alternative sands as contributions to sustainability goals in line with their core missions, financial performance and risks management (e.g. Ghassim & Bogers, 2019).

- ➔ Compatibility**: the degree to which an innovation is perceived as being consistent with existing organizational goals, current or future technical and legal constraints, values, past experiences, and needs of the potential adopters and broader social goals.** Many standards, both voluntary and legal, are likely to be a concern for early and late majority adopters: Many standards, both voluntary and legal, are likely to be a concern for early and late majority adopters: Concrete performance standards (e.g. ISO 19338:2007 – Performance and assessment requirements for design standards on structural concrete; BS EN 206:2013+A1: 2016 – Concrete: Specification, performance, production and conformity); Infrastructure project standards (e.g. the FIDIC Principles[3], World Bank's International Finance Corporate (IFC) performance standards[4], Standard for Sustainable and Resilient Infrastructure – SuRE); Building standards (e.g. International Code Council); mine tailings management voluntary disclosures, standards and regulatory changes (e.g. Global Industry Tailings Management Standard, Global Tailings Dam Portal Project). In

[3] The International Federation of Consulting Engineers (FIDIC) provides international standard forms of contract for use on national and international construction projects cover a range of issues including risk management, project sustainability management, environment, integrity management, dispute resolution techniques and insurance and a number of guides for quality-based selection, procurement and tendering procedures. https://www.fidic.org/, accessed 21 June 2021.

[4] IFC's Environmental and Social Performance Standards define IFC clients' responsibilities for managing their environmental and social risks.

addition, even if technical, economic viability and sustainability conditions are met, ore-sands will also need to be compatible with broader values and needs, including informal sectoral norms or culture (e.g. Ciganek et al., 2014 – timing; Dearden et al., 1990 – hierarchy effects; Mazzucato, 2011 – public policy-driven innovation).

➔ **Complexity: the degree to which an innovation is considered as difficult to understand and use.** Perceived complexity – not even actual complexity – can be a deterrent to adoption of new products or processes (Schlindwein & Ison, 2004). It is likely to be relevant at many different points of potential adoption of ore-sand within the sand value chain and in how these products are communicated and implications for trust building with early and late majority adopters (Molina-Castillo et al., 2012). It has been posited that where technological products or process innovations are viewed as too complex, potential adopters may fear increased transaction costs[5] – like increased uncertainty, information searches, changing supplier relationships and contracts – and require strong positive incentives to overcome them (Wang et al., 2012).

➔ **Trialability: the degree to which new ideas or innovations can be experimented for a limited time ahead of making larger commitments.** Uncertainties around relative advantage, complexity, compatibility are likely to be compounded by a few opportunities to trial ore-sand with scaling potential and observe the results. Even when relative advantage and other criteria are met, an inability to 'try before you buy' can prevent or slow the rate of adoption of a new product or process (Stryja & Satzger, 2018).

➔ **Observability: the degree to which the results of an innovation become clearly visible to decision makers and stakeholders within organizations and in industry sectors.** It is not sufficient that relative advantages and compatibility are proven – the results have to be clearly communicated to decision makers at different points in the aggregates market supply chains and individual organizations (Molina-Castillo et al., 2012). Beyond internal business decisions, perceptions of broader groups of state and non-state actors are likely to matter (Cashore, 2002), perhaps even more so in a period of growing calls for social and environmental justice in COVID-19 recovery: for example, environmental, governance and social risk issues can motivate investor behaviour (Innis & Kunz, 2020; Liekefett et al., 2021), intensify political action by local community and Indigenous Peoples and other civil society actors (Menton et al., 2021), all of whom are public policy actors engaging with both sand and mine tailings management sustainability concerns.

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[5] Transaction costs: the costs incurred in undertaking an economic exchange. Practical examples of transaction costs include the commission paid to a stockbroker for completing a share deal and the booking fee charged when purchasing concert tickets. The costs of travel and time to complete an exchange are also examples of transaction costs. The existence of transaction costs has been proposed as the explanation for many of the economic institutions that are observed. For example, it has been argued that production occurs in firms rather than through contracting via the market because this minimizes transaction costs. Transaction costs have also been used to explain why the market does not solve externality problems. See also Coase theorem; transaction cost economics.

https://www.oxfordreference.com/view/10.1093/oi/authority.20110803105309121, accessed 21 June 2021.

3 Demonstrating the possibilities

This section describes the scope and overall approach of the project, and introduces the case-study on Vale sand. The case study demonstrates a change in attitudes from treating waste as a liability to recognising its potential as a valuable resource, and helps in the investigation of real-world solutions aligned with the circular economy in the area of mine tailings management and use of alternative construction materials.

3.1 Project background and description

Objective

The aim of the project is to investigate whether co-products of mineral ores, with favourable mineralogical and physicochemical characteristics, can be a viable and sustainable source of substitute aggregate material for construction and other industries, and reduce the rising demand for sand extracted from the natural environment. Focusing on promising real-life examples, our research explores whether ore-sand from iron ore can provide a suitable, responsible and just alternative source of sand. The project includes the analysis of a real-world case-study, including sampling and testing of the material, consistent with the design of the project as a 12-month pilot. There is potential to further extend the project and to apply the methodology to other case-studies.

Assumptions underpinning project design

- If we focus on keystone actors in the construction industry – and understanding their interests, constraints, beliefs and habits – this will yield the most useful missing understanding of 'the chasm'.
- If we can reduce uncertainties around technical and economic viability (Relative advantage, Complexity, Compatibility), keystone actors are more likely to state that their beliefs are different and they intend to change behaviour. [Note: bounded by project duration].
- Even if keystone actors believe alternatives with technical and economic viability are already on the market, there will be other factors impacting adoption, including the power, interests and values of other actors.

Key questions

- Does ore-sand meet technical, environmental, economic and regulatory requirements to offset the expected increase in demand for river and marine sand in construction industry uses?
- What uses of river and marine sand in the construction industry can ore-sand substitute?
- What are the key factors likely to determine adoption of ore-sand in the mainstream aggregates market?
- How can any potential displacement impacts on traditional local sand markets be addressed to ensure a just transition, and what partnerships and business opportunities are possible with such actors?

INTRODUCING VALE SAND

Vale is a Brazilian multinational corporation and one of the world's largest producers of iron ore. It operates more than 20 iron ore mines in Brazil, generating millions of tonnes of tailings each year. Over the years, many initiatives to increase material efficiency for the recovery of iron led to an associated increase in silica content in tailings. These silica-rich tailings – essentially sand – present new opportunities for both commercialisation and reduced environmental impacts from mining. In addition, in the case of surface mining of highly weathered (oxide) ores such as iron ore, the excavated materials often contain very low concentrations of heavy metals and other elements of concern from an environmental and human health perspective. This may present an opportunity to simplify the recovery processes and broaden the options for the reuse and repurpose of these (previously) wasted materials.

One of the first dedicated sand recovery projects at Vale – the Quartz Project – was developed in 2013 by a Swiss-based staff member – Dr Emile Scheepers – in partnership with four other team members while undertaking his Executive MBA at EPFL (Swiss Federal Institute of Technology). Its purpose was to test an idea as well as commercial applications for the silica-rich material derived from mine tailings, with an estimated potential production of 10-20 Mt a year. This initiative led to the first demonstration of alternative sand application in the engineered stone industry. Engineered stone is an alternative to natural stone in household bathrooms and kitchen finishing in the construction sector. It is typically made from primary silica (93%) and resin (7%), plus added colour pigments and other aesthetic materials. The Vale silica-rich waste provided a low-cost substitute to raw quartz materials and produced engineered stone in line with industry standards (EN14617) in its resistance to stain, strength and impact. Aiming to scale this success beyond the engineered stone market, the Vale Quartz Project continued to develop and test new applications for sand by-product, including concreting, construction fill, paving, and cement manufacturing.

Most recently, an additional incentive was introduced with the introduction of stricter regulation in tailings management, including a ban on new and existing upstream type dams (the most common and low-cost option). The ban was introduced by the Brazilian government as a response to the iron ore tailings dams disasters in 2015 and 2019 and led to accelerated exploration of possibilities for Vale sand, potentially drastically reducing the amount of tailings for disposal. In 2020, Vale received its first environmental licence for the production of sand, and launched several large-scale initiatives for application of ore-sand and tailings residues in the state of Minas Gerais.

Looking into the future and responding to global efforts to address the sand challenge, Vale now also considers opportunities for the application of ore-sand worldwide. This may contribute to resolving conflicts around sand supply and avoid significant environmental damage from unsustainable practices in sand mining, in particular excessive extraction from rivers and sensitive coastal areas. As a part of this response, Vale provided funding and sand material samples for independent testing and review, aiming to facilitate the investigation of opportunities for ore-sand globally. This work is led by the Sustainable Minerals Institute at The University of Queensland (Australia), in collaboration with University of Geneva (Switzerland).

3.2 Methods and materials

We employed an exploratory approach using a mixed methods research design, in line with best research practices for evaluating transition pathways that include uncertainties around disruptive innovations (Turnheim et al., 2015; Bamburger et al., 2016).

Material characterization and testing

Rigorous and independent sampling included two steps. A preliminary sample, from a pilot-scale production, was shared by Vale in December 2020 for which basic characterisation was undertaken. Two independent samples, from an industrial full-scale operation, were collected from the Brucutu iron ore processing plant in Minas Gerais, Brazil on the 28th of July, 2021. All major testing and analysis were conducted by the Sustainable Minerals Institute at The University of Queensland, Australia, with additional testing conducted at Federal University of Minas Gerais, who assisted with the sample collection on behalf of the research team.

Stakeholder interviews

We applied a definition of stakeholders as all who might be affected by extraction of natural sand, and transition to alternative sands (Reed et al., 2009). We initially assumed a need to focus on keystone actors in the construction industry and their interests, constraints, perceptions, beliefs and habits to assist with:

- Identifying potential opportunities for circular economy solutions in the aggregates market;
- Cataloguing additional incentives and barriers to adoption of sand alternatives in the aggregates market; and
- Evolving sustainability requirements in the major use sectors, specifically targeting the construction sector.

Decisions concerning uptake of ore-sands will not depend on a single decision maker. Such decisions are widely distributed amongst organisations, individuals and groups with varying agency, and they are influenced by many other factors in market and policy environments. This process fits the description of a complex decision-making situation. We need to catalogue and understand additional incentives and barriers to adoption in major use sectors with respect to a) plural values, institutions (rules) and "rules-in-use", and b) changing sustainability trends in major use sectors, and c) artisanal and small-scale mining sector impacts and what they mean for sustainability outcomes as per best practice in sustainability science on transition planning (Scoones et al., 2021). For these reasons, we expanded to a multi-stakeholder design as a wider set of perspectives that are beneficial to understanding incentives and barriers to alternatives in regional and national contexts and contributing to sustainability assessment framework design.

The expansive number and diversity of stakeholders in the interviews generate qualitative data for analysis that contributes insights to defining the focus and boundaries of the economic, technical and sustainability assessment, as well as generating some insights for promoting ore-sand as an alternative sand to river and marine sand in construction uses.

Interviews were scheduled from January to December 2021 according to the protocol and procedures in Annex 2. A total of 21 interviews were conducted.

Table 1. Summary of stakeholder interviews (January-December 2021).

<table>
<tr><th>Interviewee profiles</th><th>Number of inter-views</th><th>Country / regional situations explored in interviews</th><th>Aggregates market players perspectives captured</th><th>Industry roles held by different interviewees</th></tr>
<tr><td>Public officials in in Kenya, Jamaica and Sierra Leone (3 national and 1 subnational government)</td><td>4</td><td rowspan="5">South East Asia
• Cambodia
• Japan
• Vietnam
Africa
• Kenya
• Nigeria
• Senegal
• Sierra Leone
America
• USA
Caribbean
• Jamaica
Europe
• France
• Netherlands
• Switzerland
• UK</td><td rowspan="5">CRH plc.
Lafarge Holcim
Jamaica Aggregates Ltd.
Bamburi Cement Ltd.
International Recycling Federation
Lathion Carrières et Garages SA
AECOM
Jan De Nul
Minerals Product Association
IRMA
Global Infrastructure Basel
British Standards Institute</td><td rowspan="5">R&D materials scientist
Global and regional sales and commercial development
Trading units (export-import and domestic procurement of raw materials)
Senior project manager
Quarry manager
Logistics expert
Sustainability lead
Recycled aggregates policy design/advocacy
Standard-setting body analyst</td></tr>
<tr><td>Aggregates market employees</td><td>8</td></tr>
<tr><td>Academics directly engaged in national sand extraction monitoring</td><td>3</td></tr>
<tr><td>Analysts in standards setting bodies</td><td>2</td></tr>
<tr><td>Civil society organisation members (Environmental & Social Justice)</td><td>4</td></tr>
</table>

Review of technical and sustainability standards and requirements

In this study we undertook a review of existing technical standards and norms in different regions for different applications of aggregate materials. The review included major international or regionally recognised standards, such as International Standards (ISO), the European Standards (EN), British Standards (BS), American Standards (ASTM), the Indian Standards (IS) and Australian Standards (AS). Different applications of sand include, for example, concreting, road base materials, land reclamation, and industrial uses of silica sand. The technical findings from the case-study in this project have been cross-compared with the standards review and other regulatory requirements.

In parallel, we overviewed existing sustainability standards and norms for different applications of aggregate materials (e.g. SuRe® Standard), focusing on major global voluntary standards in construction sector applications. In combination with stakeholder interviews, this helped us to assess the general landscape of responsible sourcing and use of sand, and potential constraints in the uptake of alternatives in the mainstream aggregate market. A full-scale assessment is beyond the scope of this report, but further investigation of the sustainability dimensions in the sand value chain is recommended, including extraction/production and transportation.

Together, this allowed us to confirm whether ore-sand can meet current norms, the definition of potential applications, as well as contribute to the development of new guidelines that may be required for making a transition across the chasm to adopting sand alternatives in the aggregates market.

Review of sand production, consumption and trade data

A review of sand production, consumption and trade was conducted with the following data sources, complemented by additional literature review (Friot and Gallagher, 2022):

- Data published by two aggregates associations. The Union European Aggregates Association (UEPG) publishes data (per type of aggregate) for Europe (EU28, EFTA, Albania, Bosnia-Herzegovina, Macedonia, Montenegro, Serbia), Israel, Russia and Turkey. The Global Aggregates Information Network (GAIN) communicates data from their member associations (22 associations over 17 major producing regions) as well as production estimates per global region.
- Two harmonized trade databases: the BACI (Base pour l'Analyse du Commerce International)[6] from CEPII and the Chatham House Resource Trade Database. Both databases include monetary values and volumes trade for natural resources and resource products, including, sand and gravel (natural sands, silica sands & quartz sands), bitumen, asphalt, among others[7]. Reporting differences between importing and exporting countries is a standard problem with trade data. The BACI dataset attempts to harmonize these differences and reports by product. Resourcetrade.earth was used in this first exploration because it provides data already aggregated by regions.
- A world economic-environment model called Exiobase[8], a Multi-Regional Input-Output model (MRIO) covering the whole world (49 countries/regions) and close to 200 sectors in 2011 (latest available year; Merciai & Schmidt, 2018; Stadler et al., 2018). This model was created by a consortium of European universities with European Union funding.

The main limitations of the above sources are:

- Although more aggregates are extracted from nature than any other material after water (UNEP, 2014), reliable data on their extraction is only available in certain industrialised countries. As a result, proxies are used with all the inherent uncertainties.

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[6] Gaulier and Zignago (2010), http://www.cepii.fr/cepii/en/bdd_modele/bdd_modele.asp.

[7] https://resourcetrade.earth/.

[8] Exiobase.eu.

Moreover, publicly available trade information draws from similar sources like the United Nations Commodity Trade Statistics Database (UN Comtrade), which is self-reported data and at times incomplete and inconsistent (see discussion in Dittrich & Bringezu, 2010: 1839).

- Input-Output Tables (IOT) used in MRIO models are generated from multiple data sources requiring harmonization between classifications and are thus only approximations which can differ from official national accounts. In addition, many countries do not provide IOT and part of the models are thus extrapolated from available data. In addition, computing global supply-consumption chains using MRIO models is subject to known biases such as aggregation biases (since a country production, trade and consumption are represented by a reduced number of sectors/product categories compared to reality) and allocation biases (due to the law of one price per sector/product category).
- A third issue is that there is no universally accepted and commonly used terminology for basic terms and definitions to model global sand availability, movement and use. Common technical standards for soil, sand and gravel overlap but are different in meaningful ways, and often vary from industry to industry and region to region which impacts how data is collected and aggregated.

Life cycle assessment

A life cycle assessment of the case-study was conducted to consider the real-world impact of ore-sand, and a number of modelled scenarios. Procedures for life cycle assessment help to balance likely and actual outcomes at the nexus of plural societal goals, values, interests and capabilities, considering different scales of social groups, geography and time and issues of rights, justice and equity (Uitto, 2021). The sustainability of material production and consumption, the environmental and social implications of the whole value chain, including post-consumption, are important considerations (EC-JRC, 2010).

Sustainability frameworks for comparing outcomes from sand sourced from the natural environment to outcomes from ore-sand do not currently exist. In this exercise, combining literature review with data from the stakeholder interviews allowed us to construct a conceptual framework that:

- Links changes in sand extraction, trade and use activities, or the use of ore-sand, to changes in environmental and social conditions, for better or worse, based on evidenced causal relationships.
- Links changes in environmental and social conditions to economic effects, impacts on vulnerable groups, and systemic-wide effects including long-term social and environmental resilience.

Given our particular concern with environmental impacts from current sand extractive practices, we want to know if switching to ore-sand is likely to reduce them significantly. To this end, we undertook a limited (i.e. cradle-to-gate) life cycle assessment (LCA)—one of the best established quantitative environmental impact assessment methods—to explore this question with published data and data made available by the Vale co-products group.

Validation and verification mechanisms

The project team established an Independent Scientific Committee which includes leading experts in sand and aggregates extraction, material analysis, distribution, use and market development. The Committee was consulted in matters such as validation of the materials characterisation and testing design, verification of the findings from the project, as well as providing additional insights and networking opportunities (see Annex C). In addition, some of the technical findings have been discussed with the stakeholder focus groups / dialogues, along with other aggregates industry players.

4 Barriers and incentives to adoption of ore-sand by mainstream aggregates market players

This section describes the barriers and incentives for early and late majority adopters based on a qualitative analysis of stakeholders perspectives (n=21) across stakeholder groups including: national government line ministries, quarry managers, logistics managers, sustainability strategy and materials innovation staff in major aggregates producers, analysts in standards setting agencies, and civil society representatives. Incentives and barriers are a function of local conditions, actor-specific needs and resources, and the applications or use for which the material is being sourced. Rather, this information shared here outlines the broad landscape within which the *relative advantages*, *compatibility*, *complexity*, *trialability* and *observability* of ore-sands would have to be demonstrated and communicated.

4.1 Relative advantages: *Why make the change to ore-sand?*

Relative advantage is the degree to which ore-sands are considered better than the preceding product, technology, concept or approach by key stakeholders in the context of market conditions. Initial background reviews pointed to technical, economic, and sustainability factors being the likely keys to understanding primary incentives and barriers for the uptake of ore-sands and mining co-products, as alternatives to sand and gravel taken from rivers, coastlines and the nearshore environment by the early and late majorities of aggregates mainstream players. The stakeholders interviewed in this project confirmed these major factors, for the most part, and complemented them with some additional perspectives.

Relative advantages in availability-transport interactions shape key incentives and barriers

The most significant reference point for aggregates market players and their clients is undoubtedly cost structures for sourcing and using sand and gravel, or cost-effective solutions for sourcing. Availability and transport were repeatedly mentioned across all stakeholder groups in different contexts as the major factors for aggregates sourcing decisions. As one interviewee remarked: "*geology is a key limiting factor in the current paradigm*" when it comes to aggregate availability; and, conversely, transport distance, modalities, network quality and fuel costs are the key enabling factors.

If aggregates are needed in a region where naturally-sourced sand and gravel are scarce, then people will pay for these materials to be transported across quite significant distances. Or, if the transport economics do not support that, a switch to alternative materials – like manufactured sand from crushed rock, recycled construction and demolition waste among other materials – can happen in a market-led transition. Twenty years of river sand overexploitation in central Kenya has reduced aggregate availability and water availability. As a result, one of the central players in the regional aggregates market introduced a new concrete mix based on manufactured sand (m-sand made from crushed rock), that conforms with Kenyan national standards, to their main concrete product lines in 2016. Today, just 5 years later, this product is the default choice unless a client specifies otherwise. The company can source m-sand at a lower price compared to river sand and passes on some savings to their customers.

Where sand and gravel are readily available, normal transport distance ranges from a few kilometres up to 50-60 km. However, in practice, transportation range depends on a number of factors and the exceptions (e.g. 100 km by road) are common enough to recommend avoiding too general a rule of thumb. The significance and acceptance of transportation costs are a function of the type of material needed and its availability or scarcity, transport mode and fuel, client preferences and their willingness to pay extra, the quality of road transport infrastructure in some contexts, and finally whether the end-application or use is high-value or low-value. Three other examples were shared by interviewees in addition to the often-quoted cases of Singapore and Dubai:

- In Moscow, the local geology cannot provide decent aggregates with the characteristics needed to produce high-strength concrete. Aggregates are imported from all over the continent, including hard rock from coastal quarries in Scotland and Norway. Indeed, these quarries are the source of hard rock for much of Europe.
- In France, high speed train ballast is used across the country but is sourced from just 12 quarries and can be transported over significant distances by rail.
- In Sierra Leone, mine tailings are known to be available and suitable as alternatives to naturally-sourced sand. They are being explored by some bauxite mining companies with the knowledge of the National Environmental Protection Agency in the context of fulfilling some commitments to local communities to develop local road infrastructure and educational facilities. However, the cost of transport is currently a barrier to extend the use of these materials in construction beyond local areas. It was even perceived as being more expensive than offshore sand sourcing (currently not used in this situation) by one knowledgeable interviewee, who considered nearshore marine sand bank mining likely to be more profitable and therefore more likely to reduce pressure on beach extraction[9].

Sand entering into the aggregates market is often aimed for concrete, yet global and regional traders will rarely transport sand for concrete applications. One exception noted in the interviews was the case of Jamaica which is exporting some sand for use as concrete raw material to other islands in the Caribbean. The Pacific is another location where such transport occurs.

Relative advantages of scale/volumes is not necessarily a strong incentive for aggregate industry players until the material has been proven

Sourcing decisions, including the decision of which materials and how far to transport them, are weighed against urgency, importance and profitability on a project-by-project basis. One perspective that emerged was that the quantity of alternative aggregates is not an issue in regions where recycled aggregates are available – where there is a great deal of construction and demolition waste, for example. The issue is in the applications for which that alternative material can be used successfully. For example, the EU Waste Directive and national legislative

[9] Sand mining in the active nearshore beach system usually does have a direct environmental impact on the beach

and economic instruments instituted new protocols to reduce construction and demolition waste going to landfill are creating pressure to find more commercial applications for this material. However, not all construction and demolition waste are suitable, or can be easily made suitable, to displace naturally-sourced sand and gravel. A number of Europe-based interviewees raised the need to find a solution for some technical solutions, including local construction standards and building codes that currently do not allow and block the greater use of available recycled aggregate in construction applications

A missing perspective here is that of major project developers in regions where recycled aggregates are not available in large volumes, i.e. where built environments are not mature enough to be considered 'urban mines'.

Relative advantages on sustainability outcomes are desirable but they are, in practice, incompletely considered and not perceived as an essential part of materials offering in local markets

"Circular economy is also a focus for us, a focus for the majority of people working in my company because we do understand how important this is". This sentiment from one interviewee reflects the view and opinion of a number of industry interviewees that are operating on a strategic level for aggregates players.

However, sustainability goals seem to be largely viewed through the lens of carbon emissions and not on the place-based or ecological system basis that is more likely to reflect the extent of social and environmental impacts that can occur when sourcing sand and gravel from rivers, lakes, coastlines and nearshore environments. And while shifts may be happening in the largest of the mainstream players, sustainability concerns are considered after economic costs and benefits for most people in contexts where construction and development are seen as critical non-negotiables.

Finally, sustainability concerns and circular economy policies are generating interest and investment in a range of alternative materials already strongly present in mainstream regional and domestic markets. These include traditional building materials, manufactured and recycled aggregates, and new materials emerging out of local settings in response to local supply or waste management issues. This implies that ore-sands have to demonstrate relative advantages or complementary characteristics to both naturally-sourced sand and a wide range of alternative materials already known and used.

4.2 Compatibility: *Do ore-sands match my constraints, needs and expectations in a given situation?*

Compatibility is the degree to which ore-sands are perceived as being consistent with existing organisational goals, current or future technical and legal constraints, values, past experiences, and needs of the potential adopters and broader social goals. Background reviews have already highlighted the need for compatibility with technical standards, legal and regulatory requirements and more intangible sets of values. Stakeholders interviewed confirm these major factors, for the most part, and complement with additional perspectives.

Compatibility with performance goals is a key factor shaping incentives and barriers

There was a sentiment expressed in many interviews that river sand in particular is a hard material to beat for performance in applications for making cement and concrete. This sentiment is not only a question of meeting legislative requirements or technical performance standards, however. There are many decisions and decision makers to consider when adopting an alternative, including the different types of performance goals:

Technical performance standards for concrete and construction: While meeting current standards is needed to enter the market, stakeholders also shared that materials science is an evolving science and the norms are updated regularly, and in certain regions. There is a live conversation around performance-based vs ingredient-based standards for concrete and cement, as one example. One interviewee remarked, giving the example of how concrete norms have been changed to reduce clinker use to reduce CO_2 emissions in cement production, how norms are changing (*"we no longer use Portland cement as the norm"*) as materials technology innovation occurs: "*I know it looks like the cement and concrete industry moves very slow – maybe for some cases that is true – but in terms of the properties of a material I think there's really a huge driving force in making changes because there are advantages for everybody[….] We are moving and we are moving faster than people think".* Ultimately, technical norms are in place to help an alternative reach a certain technical performance – but industry innovation is moving beyond the established norms in cement and concrete production. The underlying performance criteria driving experimentation for high-performance applications include: durability (*"a concrete must last at least 50 years"*); water absorption problems for using recycled aggregates with real world conditions leading to issues with concrete consistency (*"this is the killer"*); on the other hand, the fresh state concrete must be liquid and easy to spread (essential to workers). Where high-performance is required, more than one stakeholder expressed preferences to continue working with virgin naturally-sourced material and avoid alternative materials. Where a lower performance is required, and building codes/ construction standards would allow, this is the opportunity for alternatives to be used instead of river and marine sand and gravel.

Client-demanded sustainability performance: Major aggregates firms are experiencing a mix of drivers on sustainability performances: political and policy in some cases, but social drivers of client or consumer questions and requests seem to be moving major firms ahead of any political momentum or legislative push on sustainability. The CO_2 emission reduction performance has driven some strong market demand for green concretes, and environmental concerns have driven design and materials selection in some high-profile projects (one stakeholder mentioned the construction for Google in California). There is a perception gathered from the aggregates market interviews that energy use and associated carbon emissions create a greater negative environmental sustainability impact than in extractive phases.

Circular economy performance targets: For example, in Switzerland, there is a legislative requirement that obliges new construction to include 20% recycled aggregates that is driving increased uptake of alternative materials, even to the point where they are transported long distances to fulfil quotas. Where such circular economy instruments (other examples in the interviews include UK aggregates tax and landfill tax combination) favour alternative materials, they are largely focussed on recycled aggregates from construction and demolition waste streams.

Compatibility with the 'direction of travel' of the public policy environment

Broadly speaking, two basic value structures emerged in interviews to describe policy environments: 1) those weighted towards naturally-sourced sand extraction because it is impossible to envision not building what needs to be built, and 2) those leaning towards green and circular economic systems either because loss of resilience and resource security or because of anticipatory stances. In the latter, ore-sands are compatible with policy goals and incentives for uptake increase because institutions, structures and processes shape the landscape to make it so. However, the barriers are high in the first structure – so much so that the relative availability, economic and other advantages must be incontestable and perhaps benefits shared strategically with beneficiaries of the current status quo. Many people benefit from the current system of naturally-sourced sand extraction – from small scale miners, local institutions ('head men' of the villages, local municipalities/sub-national governments) who extract rents, local construction companies, larger industry groups – some of these groups will need to see observable results for economic security and livelihoods from alternatives or some equivalent or better situation.

The place naturally-sourced sand and gravel holds in many economies is a complicated one. National governments are key in high-value mineral resource extraction dynamics but subnational governments are playing a more significant role in driving both overexploitation and the shift to more responsible sourcing of sand and gravel. Much depends on the ability to transport large volumes of materials (the available infrastructure), financial structures of public budgets, mandates and overall availability of resources for enforcement, which are influenced by the degree of vertical integration of public administrations and the tendency for decentralised governance. Extraction rents are a major source of revenue for some subnational government agencies, but it is overlooked by key line ministries with stakes in regulating sand mining because it is not a high-value mineral resource.

Negative externalities are too common. Environmental impact assessments, extraction permits and restoration/rehabilitation requirements in extraction concessions are the primary regulatory instruments to identify and manage social impact, ecological integrity, biodiversity impacts and other environmental sustainability concerns. Where resources and incentives are in place in the policy environment, these instruments function to constrain resource access successfully (though rehabilitation seems to be a concern in many locations). However, more often than not, interviewees raised issues about the poor quality of environmental impact assessments, conflict of interests involving those who conduct them, the absence of permitting rationales, plans and volumetric monitoring relative to real situations of sand availability, and remarked that rehabilitation was rarely required. The shortfalls of these instruments affect the opportunities to influence the economics of sourcing sand from the natural environment and therefore the incentives and barriers for alternatives.

Public policy leadership shapes incentives and disincentives strongly when it has the buy-in from citizens. It is worth highlighting that improvements have happened in sand management even in contexts of generally poor regulatory enforcement when other basic resource threats have emerged locally from sand exploitation. One example surfaced in interviews was how water quality and availability in Kenya impact the scarcity of aggregates for local development. Resource flows from outside the county for construction in Nairobi and the Nairobi-Mombasa transport corridor have motivated the creation of the Makueni County Sand Conservation and Utilization Authority.[10] The authority regulates access to local sand resources and prioritises extraction for local development purposes and recovers cost of their operations through a fee-based system which is implemented on anything above 2 tonnes extracted from specific approved sites. Successful management was credited to the strong community support and buy-in secured in part through participatory monitoring committees which determine where and how much sand can be extracted.

Compatibility with private voluntary or informal norms & standards

Additional elements raised in interviews linked to compatibility with values, needs, expectations and interests include compatibility with:

Internal stakeholders – organisational business models and mindsets: Introducing ore-sands to product lines can be easier or harder depending on whether the organisation considers their core mission to produce and trade naturally-sourced materials or developing products and services that can draw upon a *"family of aggregates",* as it was termed by one industry interviewee based in Europe*.* Indeed, some European stakeholders seemed to hold the perspective that alternatives were already well embedded in the market (fly ash, bottom ash, construction and demolition waste, slag sand – though these are largely acknowledged as substitutes within cement production and not in concrete production, which is perhaps the largest consumption application of sand). The issue is more that these materials demonstrate fundamental technical and cost challenges, and lack some basic enabling policy conditions including adoption of already established or well-proven policy instruments for encouraging circular economy processes in waste management`.

Internal stakeholders – Laborer expectations and needs for working with concrete material. Laborers, and on the ground workers, are critical stakeholders who can advocate for or block new materials uptake ("*they are not important, they are essential"*). Also, without training and their buy-in, laborers can also harm the wider perception of ore-sand technical performance by mixing and using alternative sand concretes incorrectly, creating poorer quality products.

Personal interests of powerful actors. In two national cases, stakeholders mentioned the important role of the informal use of political power by national and subnational level politicians in reducing or preventing extraction from beaches in areas where they own property, either for personal use or as investments.

"Bread and butter" goals of achieving basic social security and maintaining stable societies. Whatever is going to be done, it has to consider local livelihoods. No matter how good the objectives are, if it threatens additional poverty or economic burdens for vulnerable people, it will not gain support. One stakeholder's reflection: *"There is this notion that we can't do without sand, and that we can do without using sand as a way of livelihood, and therefore going that*

[10] Makueni County Sand Conservation and Utilization Act, 2015.

route to regulate it in a strict sense might cause chaos". In line with the *Mosi-oa-Tunya Declaration on Artisanal and Small-scale Mining, Quarrying and Development* (Franks et al., 2020) it is critical that any change process with the potential to impact artisanal and small-scale miners, involves those very same miners in the decision-making from the outset.

Aspirational consumption goals for building with concrete. Strong incentives to build with concrete rather than traditional building materials that surfaced in all three interviews reflect concerns about durability of traditional materials, status-seeking behaviours, conformity with perceived and actual emerging social norms and a desire for contemporary design.

4.3 Complexity: *Will ore-sand be easy to use?*

The degree to which ore-sands are considered as difficult to understand and use must consider some varied perspectives that shape incentives and barriers. Some examples raised in interviews include:

Operations and logistics of working with recycled aggregates are more complicated than working with virgin material sourced from rivers. This is a barrier to uptake beyond what use of recycled materials is required legally.

Changes in well-established practices. Any additional processes or changes in existing processes (i.e. concrete mixes) required to use ore-sands compared to river sand run the risk of noncompliance and negative perceptions about the quality of application performance achieved with ore-sand. Training and capacity building for masons and laborers were recommended based on the Kenyan example of a transition to manufactured sand.

Environmental pollution concerns from materials associated with mining. Concerns about having to treat mine tailings for toxic elements or other pollutants come quickly to the mind of nontechnical actors when ore-sands from mine tailings are mentioned, justifying the need to clarify the difference between the use of tailings residues as sand, *vis-à-vis* the production of sand by-products from mineral ores.

Regulatory and coordination complexity. This is already a challenge for naturally-sourced sand and gravel and for using bottom ash, recycled aggregates and other alternative products in some jurisdictions. Perhaps this can work as an incentive to shift to ore-sands if the relative complexity is proven to be lower for users.

4.4 Trialability: *What kind of 'try before you buy' factors matter most for ore-sands?*

Trialability generally means the degree to which new ideas or innovations are experimented for a limited time period, i.e. perceived ease/usefulness, voluntariness, image and membership. Uncertainties around relative advantage, complexity, compatibility are being compounded by a few opportunities to test ore-sands in the mainstream market. The project team started out with the view that the scale of mine tailing volumes is likely to be perceived as an advantage to market actors. However, the interviews with the aggregates actors suggested that communicating the potential volumes of ore-sands may actually create hesitance initially. As one aggregates sector actor drew on a parallel example of steel slag when it was first exported from Europe (Germany) to Africa (Nigeria), as a material that was new and not well understood in the importing market - though one with proven technical and economic benefits:

"When people are buying imported material, it's normally in large quantities. The average size of a cargo is going to be 30-40,000 tonnes of material. It's a huge amount of material. So, it's a big commitment to take something for the first time. If you haven't used it before, you don't know how it's going to go. No matter how great a story I tell you, to spend several million dollars on 30-40,000 tonnes of material is a big commitment. So, we would often come up against people who were reluctant because it hadn't been done before in that country. They hadn't used that material. So, they wanted to sit back and wait until someone else had done it."

4.5 Observability: *What are the performance factors around which ore-sands need to show proven results?*

The degree to which positive outcomes from using ore-sands need to be clearly visible to the potential users of that material, as well as other stakeholders who influence the incentives and barriers to its adoption. The following perspectives emerged from the qualitative data analysis:

- **Proving relative advantages to internal stakeholders in aggregates market firms:** Since the primary drivers are largely economic in nature, results around profitability of ore-sands, a likely future of growing demand for these materials, their contribution to preparedness for adapting to changing regulatory environments with circular economy motivations, all seem critically important to communicate.
- **Tangible demonstrations to aggregates clients that ore-sand can be used as an alternative to river, lacustrine and marine sand.** Other alternatives are better known and trusted. Ore-sands are a brand-new concept for many. They also have some risk perception hurdles to overcome by their association with the primary material extraction sector with already complex society and environment interactions, and some poor track records in mitigating environmental and social impacts.
- **Proven possibilities for providing livelihoods equivalent to or better than sand extraction.** The benefits of sourcing sand and gravel from the natural environment are currently very visible for many stakeholders: generating livelihoods, providing desirable concrete for building. These stakeholders, however, do not see the downsides of such a transition. If the international community or any actor starts to talk about change on the ground for responsible sand sourcing and management, it needs to be ready with a plan and resources to manage expectations and concerns carefully with real possibilities to support economic activities that are the equivalent or better than those that are currently being supported through sand extraction. This is an imperative in a COVID-19 context where sand extraction is providing cash-in-hand jobs for younger people with daily incomes in economies where other livelihood sectors like tourism have been severely impacted by the global pandemic.
- **Contribution to national development goals, policies and plans.** If ore-sands want national government support, they will need to secure allies within national line ministries related to mining, transport and infrastructure, environment and natural resource management based on the potential for high-value applications.

- **Contribution to improving equity outcomes.** The theme of equity came up in a number of distinct ways. One stakeholder expressed how those who can afford to use or promote ore-sands should be the ones to do it, giving the example of mining companies who the interviewee thought should bear the cost of increasing the availability (and reducing the cost) of ore-sand. A second stakeholder mentioned the injustice of sand being extracted and transported out of localities for development gains elsewhere. There are also equity considerations related to sand extraction. On the one hand there is a potential that ore-sand could displace artisanal and small-scale miners who may rely on informal sand extraction as a livelihood in circumstances of poverty. This might manifest where the introduction of ore-sand is at greater volumes than any expected increases in future demand for sand. Displacement may meet the desired goal of reducing the pressure of sand extraction from dynamic natural systems where environmental impacts are greatest, but if not accompanied by a just transition it is unlikely to result in an equitable outcome. On the other hand, where local communities are standing up to overexploitation of naturally-sourced sand and gravel by elite actors, part of the underlying motivation is the unfairness of a situation whereby only a few individuals are benefiting from what is generally a publicly-owned resource. In such cases benefits may not be shared with the community and, worse, they can also reduce the availability of other public or common goods like water, or aggregates for local use.

4.6 Opportunities for adoption of ore-sands in mainstream markets

Stakeholder data suggests that the **most critical factor** for adoption of ore-sands in mainstream markets is *relative economic advantage*. This is however not simply a question of ensuring alternatives are cheaper than conventional aggregates. Relative advantage here goes beyond accounting cost to include opportunity costs of foregoing aggregate consumption, i.e. project failures; the value derived from managing potential future supply constraints and ensuring consistency in materials inputs; avoiding reputational risks; etc. Stakeholder engagement has also confirmed that sand sourcing and material efficiency are currently poorly addressed across sustainability standards. From our analysis, stakeholder perspectives generated several insights essential to any strategy for introducing ore-sands to mainstream aggregates markets. In addition, evolving sustainability requirements in the major use sectors (including construction) can be a gateway for ore-sands to enter mainstream aggregates markets.

Developing a niche

If it can be shown that ore-sands add niche value in key construction sector activities, incentives are likely to emerge for the uptake at scale as it has for other alternatives in some regional/national aggregates markets. Solving real problems for the sector is a way in.

Introducing ore-sands into aggregates markets requires developing and honing a well-crafted market niche in the construction industry emphasising the alternative's sustainability credentials. This entails telling an authentic story, for example emphasising ore-sand's ability to abide by sustainability standards. Simultaneously, it requires showcasing this circular economy solution's net sustainability impact when sourced for construction projects.

Aggregates market players increasingly perceive strong calls to engage in sustainability certification processes across the sand value chain, including for extraction, transport, and construction sector applications. It reflects how the aggregates sourcing landscape is changing, "*Back then, cost was the main concern for our projects, we're now adding sustainability*" (Aggregates market analyst). Carbon reduction is increasingly becoming part of construction companies' tender applications and is often embedded within sustainability criteria to win contracts.

Finding allies and engaging in cross-sectoral dialogue

Who are the allies who can help construct a bridge over the Chasm by: a) changing current narratives about sand from natural sources being the ideal (river sand in particular), to talking about "a family of aggregates" that includes alternatives as common place, b) supporting demonstration of the material in use, c) shaping the conversation on circular economy in mineral resources and construction applications.

Engaging in cross-sectoral dialogues with industries and standard-setting institutes with an interest in sand and gravel procurement offers multiple opportunities for introducing alternative sands into the aggregates markets. Potential allies include new market partners, including standard-setting institutes who can facilitate setting-up new opportunities to research, test and promote ore-sand's adoption.

As confirmed by stakeholder interviews with aggregates market players, to cross the innovation chasm it is essential to promote pilot projects with real world results that showcase the material's easy-win and replicability, with an emphasis on the material's performance, durability, and sourcing process. These lesson-learning, stakeholder engagement and networking opportunities will help provide real-world testimonies to alternatives' potential.

One opportunity to find allies is namely to engage with regulatory authorities as market partners. When issuing contracts for construction projects, governments and regulatory authorities increasingly seek to incorporate a sustainability dimension into the procurement process. Such a sustainability dimension can namely include the use of alternative construction materials in projects.

One avenue for finding such allies amongst regulatory authorities is through construction projects targeting to be recognized as 'sustainable infrastructure' (UNEP 2021b). Sustainable infrastructure projects are often anchored within local authorities' regional decarbonisation and longer-term development strategy. These project tenders embed sustainability criteria into the evaluation phase, giving more weight to sustainability factors and performance-based criteria when awarding contracts.

Finding such allies within the sustainable infrastructure landscape can help build a shared pragmatic narrative around ore-sand as a material procured in sustainable infrastructure, in line with end-users' organisational goals, values and past experiences.

Reframing the agenda

Sustainability factors are important. However, how positive and negative impacts are considered and accounted for currently in the sector are unlikely to create strong incentives for alternatives. The current emphasis is on CO_2 emission reduction and the risks posed by observable inaction on climate change, which may or may not be sufficient to change the agenda for ore-sands. The debate needs to include environmental and social impacts and risks they pose for different stakeholders, translated into economic impacts and risks for adjacent economic sectors in sand extraction zones and their downstream, including informal sectors that are supporting livelihoods and societal stability.

Sustainability is increasingly a key factor in aggregates sourcing practices and decision-making. As our interviews confirmed, altering how buildings are designed and constructed require changing aggregates sourcing processes. Time, cost, and legislative requirements are often the main factors defining which materials are used.

One way to reframe the agenda is to collaborate with standard setting institutes to reset norms so as to promote the inclusion of sand sourcing and efficiency considerations into accredited sustainability standards, namely those focused on construction end-use applications.

If the standards allow for the use of ore-sands, it will incentivise interest, especially during the project's design phase. However, the main challenge for ore-sands to cross the chasm remains at the issue of certification in line with local technical standards and performance requirements.

"A lot of the solutions we've led people to, their response has been to us it will take 10 or 20 years before these materials have the same local certification in place for us to use them".

Enabling access

Meeting the technical standards that are gateways for market access is not a concern for the stakeholders interviewed, since these standards are performance-based. To strengthen incentives, the mainstream market needs ways to access alternative aggregate materials/products that are a) ideally, built into existing supply chains and distribution processes to reduce complexity of switching to the alternative, or b) cost competitive so that the transaction costs implied in changing sourcing procedures can be overcome by a profitability argument. Finally, two critical constituencies who need to be aware of the alternative and convinced of its benefits include people selling and working with the materials on-the-ground.

Giving the mainstream market ways to access ore-sands requires re-thinking sourcing practices. Stakeholder perspectives generated insights for three entry points in introducing ore-sands into existing sourcing practices:

- **What supply chain management does the project have in place?** Sustainable sourcing practices should go in-hand where possible, the public disclosure of aggregates sourcing practices of contractors, sub-contractors, and primary suppliers.
- **Where is the project getting the materials from?** Incorporating sustainable sourcing practices increasingly matters to clients in larger construction projects. Implementing such sustainable sourcing practices implies sourcing-where possible-from recycled materials and/or by-product synergies. Simultaneously, it implies sourcing materials at the minimal distance, ideally from regions in the proximity, all where cost-effective and financially feasible to do so.
- **Is the project using the material wisely**? Incorporating sustainable sourcing practices likewise implies the need for material resource efficiency, such as using alternative materials, whenever it is financially feasible and cost-effective to do so.

Barriers: We have placed a lot of emphasis on how to bridge the innovation chasm, but it is also worth considering how to address 'trolls' that might be present under that bridge, such as vested interests, structures governing trade and distribution in supply chains.

Overcoming these barriers could be another challenge for ore-sand to access the market in the early days.

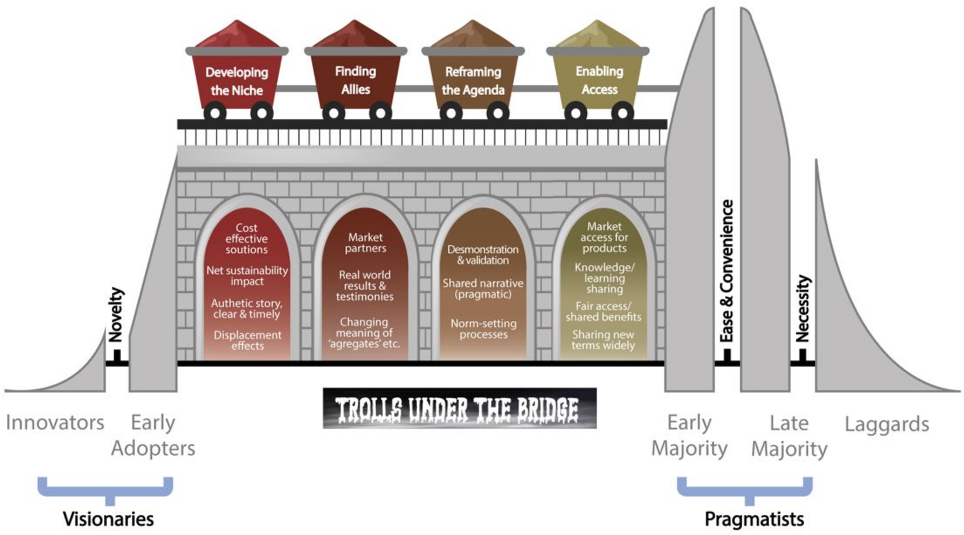

FIGURE 2. AN OVERVIEW OF ELEMENTS NEEDED TO 'CROSS THE CHASM' IN INNOVATION ADOPTION OF ORE-SANDS.

Adapted from: (Polhill et al., 2019).

5 Sand products and markets

This section overviews major properties and requirements for different types of sand used in the construction sector and industrial applications, and the role of technical standards.

5.1 Major areas of application

Sand and gravel are very broad groups of materials which are usually extracted and used locally. They are versatile but depending on their use, they can be subject to stringent requirements. Whether a material can be considered as a product or viable alternative to sand and gravel often depends not just on its technical performance, but also regulatory requirements, environmental impacts, as well as cost and proximity to market.

The three major (economically significant) end-user groups for sand products include:

- Construction;
- Land reclamation and restoration; and
- Industrial applications.

In addition, ecosystem services and agriculture are also important applications. Each end-user group has its own set of standards and practices and often relies on a specialized sand producer for their supply. However, this does not exclude the fact that certain large-scale producers/suppliers work across several fields.

5.2 Sand products for different applications

Different areas of application may seek different properties from sand and aggregate materials, resulting in rather unique products supplied to the market. In general, however, there are three major types of properties and characteristics that the end-users take into account:

- Physical: shape, colour, particle size distribution, density and other mechanical characteristics;
- Chemical: pH, mineralogical and chemical composition, organic content, etc.; and
- Environmental: toxicity, bacteriology, specific contaminants, compatibility with target eco-system.

For industrial applications, consistency of the material characteristics is equally important, while for large scale projects of any nature, continuity of supply can be crucial. However, what type of sand is used for which application is often determined by traditions in construction and industrial applications, which in turn have evolved with different locally available raw materials, geographical conditions and measurement systems. Several of these traditions have evolved into norms, standards or codes and were subsequently replicated by various other regions (UNEP/GRID-Geneva, 2021).

Construction

Construction related applications are by far the biggest market for sand (both in volume and value). Sand is mainly tested for its physical properties, while chemical characteristics are identified to determine whether chemical processes or reactions might negatively affect the physical/mechanical integrity of the structure or end product over its envisaged lifespan. The environmental impact from a user perspective is only tested if there are prior concerns or indications that the sand might be a source of pollution.

The key physical characteristics of interest for construction sand or fine aggregates include the particle size distribution, abrasion resistance, grain shape, resistance to crushing, water absorption and percentage of fines smaller than 75 microns or 63 microns (Harben 2002; Evans 2009). The grain size distribution, percentage of fines and shape are, however, the three most important parameters. Applications which require medium to coarse sand usually come with clear upper and lower limits for the particle size distribution whereas applications that accept fine to medium sand usually only indicate a single upper value for the percentage of fines and coarse material. For most construction applications, subangular and angular sand are preferred.

In construction and infrastructure work there are many “types” of sand. The type of sand is usually named after the application it is intended for or the source of sand it is derived from e.g. infill sand, masonry sand and ready-mix construction sand. The specification of these sand types vary from region to region (see below section on Technical standards and norms).

Land reclamation and restoration

Similar to construction applications, sand used for land reclamation and restoration purposes is mainly tested for its physical properties. Although, additional checks are required for harmful trace elements (e.g. lead, arsenic, mercury), potential changes in chemical properties (e.g. pH in water), and the amount of fines to be introduced into the environment. Another important characteristic is the material’s compatibility with the environment where it is introduced and how this may affect the ecosystem dynamics.

There are three major types of direct sand use for reclamation and restoration:

- Beach nourishment and habitat restoration;
- Sand bodies which require a high retaining and/or bearing capacity and need to be compacted, e.g. sand bunds/quay and certain types of “sand foundations”;
- Infill material.

In beach nourishment and habitat restoration, the original (native) sand has certain characteristics, including mineralogy, composition, and grain size which are to some extent in equilibrium with the local conditions (Dean & Dalrymple, 2004). The same is true for other dynamic ecosystems such as rivers and lakes. Even if these environments are in erosion, the original sand provides an indication of what type of sand would be stable in that particular environment (e.g. Dean & Dalrymple, 2004; Speybroeck et al., 2006). Moreover, the ecosystem is to an extent adapted to the conditions shaped by a certain type of sediment. In order to avoid adverse effects on the river and coastal fauna, the dredging industry has to use the sediment (sand) that closely matches the target environment (Greene, 2002). The sand is not only important for its direct effects on the ecosystem but also for the longevity of e.g. the beach. It defines how well the system can withstand the cumulative impacts of storm events, waves and/or climate and thus how soon this beach will need to be renourished again (e.g. Dean & Dalrymple, 2004; Speybroeck et al., 2006). In practice, this generally means that sand needed for beach nourishment and habitat restoration has to be approached on a case-by-case basis.

Land reclamation projects usually require highly compactable sand and infill material. The fill material is usually sandy material which is pumped or placed into an area retained by a wall of compacted sand, called the bund or retaining quay. The fill material makes the bulk of sand used for this application. Generally fill material consists of free-draining sand with particle sizes in the range of 100 to 600 µm (e.g. BS 6349-5). In most cases, the retaining quays require highly compactable medium to coarse sand, used in smaller volumes. The precise specifications depend on the required bearing capacity, slope stability, the technique used for placement and/or time needed for the material to settle and compact, environmental requirements and the risk of erosion, flooding and liquefaction. The major requirements for infill material relate to sufficient stiffness, shear strength (i.e. resistance against deformation) and drainage. The requirements for the compactable sand tend to be more strict as it needs to provide a higher bearing capacity and retaining strength. In the last decades, major technical progress has been made in the design of artificial islands to allow for various types of fill material including fine sand.

Industrial applications

In contrast to construction and land reclamation, physical, mineralogical and chemical properties are equally important for industrial applications of sand. Silica based sand is the most important form of industrial sand, and the main focus of this project, but other types of sand are also widely used, e.g. olivine, chromite, staurolite and zircon sands (e.g. Brown, 2000; USGS, 2021). Industrial applications typically require a much higher silica content than construction sand, to distinguish between industrial grade sand and construction sand, 'silica sand' is a widely accepted term for industrial sand with a high silica content.

Silica sand has a very broad range of applications. According to the report by Freedonia 'World Industrial Silica Sand Report 2016' (in Sibelco, 2019), industrial sand production is mainly driven by five sectors: glass (34%), foundry (22%), oil & gas (20%), high end building materials and ceramics (7%), and chemicals (6%). Also the sports industry is a growing market for industrial grade sand. Silica sand is used for football pitches, golf courses and in equestrian sports. In glass making, sand is the principal source of SiO_2. It is digested together with various additives in the melting process for various kinds of glass including fiberglass, flint container glass, flat glass and optical glass, glass wool and a large variety of specialty glasses (Scalet et al., 2012; GWP, 2010; Harben, 2002; Di Pierro, 2021).

The percentage of SiO_2 and Fe_2O_3 are in many ways the overall key measures for silica sand quality. The higher the percentage of silica, the easier it becomes for a producer to use the sand as a quality source of SiO_2. Iron (Fe_2O_3) on the other hand is undesirable for several different reasons. In glassmaking, iron oxides need to be present at the lowest possible concentration given their strong absorption bands (Di Pierro, 2021), in particular for those glasses where optical transmission must be optimized such as the sheets protecting silicon wafers from oxidation in solar panels. In foundry sand used to create moulds and cores for iron casting, iron impurities reduce the refractoriness, in other words it makes the sand more susceptible to melt (Harben, 2002). In optical fibers they impair transmission; and this adversely affects the production of pure silicon products (Boussaa et al., 2017). Depending on the application, other impurities (e.g. Al_2O_3, K_2O, MgO, CaO, Na_2O, TiO_2, Cr, Pb) may also need to be closely monitored given their effects either on the melting process or optical properties of the final product.

The importance of the physical characteristics of the sand cannot be neglected but the requirements are more diverse and less easily captured in a graph. For the production of glass, the grain size distribution has an important effect on the melting process and the homogeneity of the resulting glass; for foundry sand, rounded to subangular sand with medium to high sphericity gives a better flowability and permeability with high strength at low binder additions and the use of finer sand in moulds yield a better surface finish (Brown, 2000); for equestrian surfaces non-staining, very fine to fine sub-angular to angular sand with a low sphericity and negligible fines content is preferred (GWP, 2010); etc.

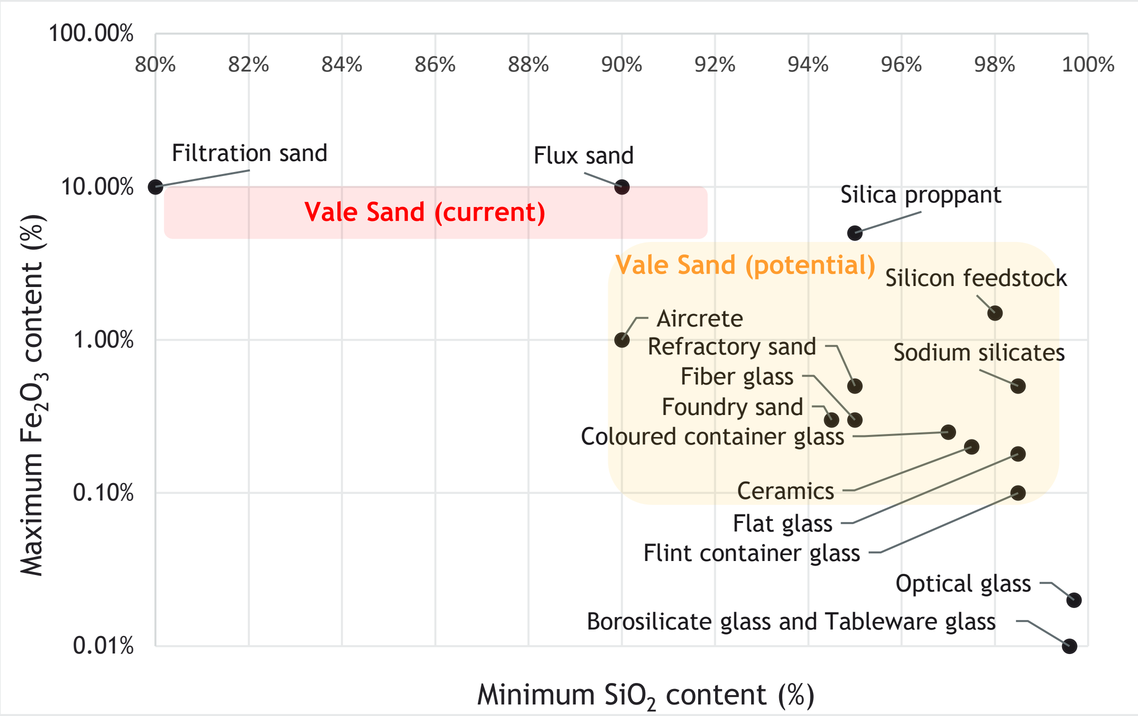

FIGURE 3. MINIMUM SiO_2 AND MAXIMUM Fe_2O_3 CONTENTS IN SAND FOR INDUSTRIAL APPLICATIONS.

Notes: 1) this graph is not inclusive of all properties required for specific applications; 2) Vale sand (current and potential) is presented on the graph for indicative purposes only (refer to Section 7).

5.3 Alternative sources of sand

Sand is used for a very wide variety of applications and they are constrained by factors which are regionally determined (see section 5.2). The sustainability issue around sand extraction and use will therefore not be resolved by one single alternative but will require a mix of alternative sources to cover the different regions, and technical and environmental requirements.

The materials from alternative sources fall into three groups including (1) crushed rock (2) recycled materials and (3) co- and by-products from industrial or extractive processes.

Crushed rock is a primary raw material and is the main alternative both in the construction and in other industries using industrial grade sand. Although a substitute, it remains a primary resource requiring extraction with environmental impacts. Crushed rock based sand is often limited to certain applications due to the relatively high percentage of silt and clay and the grains' angularity, and often requires blending with naturally-sourced sand. Moreover, it is also not always available where it is needed most, requiring dedicated transport infrastructure – often rail or sea – to provide the economies of scale needed to allow it to access its markets.

Recycled materials stem from a variety of waste sources. These sources usually need treatment to become fit for the intended use. Products resulting from treatment are sand, gravel or aggregates, both in varying qualities. Aggregates derived from recycling construction and demolition waste from buildings and infrastructure are the most used recycled substitute. Another example is the production of aggregates from incinerator bottom ash. By classifying and removing metals, good grade material can be obtained to replace sand in road construction. Other materials include recycled ceramics, expanded slack, expanded perlites, treated dredging spoil, and cleaned excavated soil. Recycled material is an important source of sand for countries which are well urbanized and have a well-developed infrastructure. However even in these regions supply is seldom fully covered by recycled material. Regions whose infrastructure is growing rapidly or are not very urbanized usually have less material to recycle and face logistical issues to recycle their waste. These regions usually have to rely on other sources. The use of recycled materials has the important added benefit of reducing the amount of waste.

Co- and by-products from industrial and extractive processes are a group of secondary materials that are made while manufacturing or synthesizing something else but which can be beneficially used to replace sand and/or gravel. An example is the ore-sand studied in this project, a deliberate by-product from crushing, grinding and mineral processing of different mineral ores to achieve the required properties of sand. Other examples include metallurgical and mineral slags. Some of the by-products need further treatment in order to meet specifications. Large scale industrial and extractive processes are not always in proximity to the market. Depending on the industrial or extractive process, transport infrastructure such as rail, river or sea transport may be in place to provide the economies of scale needed to allow it to access its markets. The use of co- and by-products has the important added benefit that the production of waste is avoided.

5.4 Technical standards and codes

The role of technical standards is to make sure products conform with certain quality requirements for specific purposes. They may also help ensure that an end-product or process is compatible with the intended uses or regulation across a certain industry or region.

Standards can thus be used to enhance or avoid market-based competition by ensuring or avoiding the interoperability of complementary products. As a consequence, they reduce or increase costs, improve safety, and enhance environmental outcomes.

Technical standards and codes generally play an important role in the construction and manufacturing industry. They are usually a result of different building/production traditions, which in turn are related to measurement systems, geographical/ environmental conditions and the historic or current availability of raw materials. (UNEP/GRID-Geneva,2021).

Most standards are voluntary, in that they are instruments produced for the convenience of those who wish to use them. Standards are however often used in commercial contracts, in which case they are not exempt from being used in legal proceedings. Standards can also be mandatory when they are referenced in legislation (COPOLCO, n.d.). For example in India, cement needs to be certified (Bureau of Indian Standards, 2018 November 2). For masonry cement to be certified in India, it needs to comply with the Indian Standard "IS 3466:1988 Specification for masonry cement". The sand used thereby needs to conform to "IS 650:1966 'Specification for standard sand for testing of cement."

Moreover, in certain regions and countries, there are legal consequences for not complying with *voluntary* national standards. For example, manufacturers may have to prove that they conform with legislative requirements in the case that they do not comply with voluntary national standards. In this case, manufacturers have thus a choice between complying with the standard and proving legal compliance without meeting the standard. This is for example the case in the European Economic Area, as per the 'New Approach Directives' (CEN, 2019, June 14). The CE-mark is used for aggregates, in legal compliance with the requirements under the EU's harmonized standards (MPA, n.d.).

There are a wide variety of standard setting bodies. Our engagement with the construction and dredging industry shows that ASTM, BS and ISO standards are the three internationally used standards, and the most referred to in international tender processes for large infrastructure projects. In this context, these standards are often used as "construction codes" to be followed by the contractor and audited by the client's lead engineer. The implications of these technical standards' are as follow:

1. **ASTM International.** ASTM International is one of the largest voluntary standards developing organizations in the world. As a not-for-profit organisation headquartered in the United States, ASTM provides a forum for the development and publication of international voluntary consensus standards for materials, products, systems and services. Its volunteer members represent producers, users, consumers, government, and academia from more than 140 countries (ASTM International, n.d.). The organisation is often confused with the American National Standards Institute (ANSI), who unlike many other national standard institutes, does not write standards. Instead the ANSI coordinates and accredits the development of voluntary consensus standards in the United States, and represents the needs and views of U.S. stakeholders in standardization forums including at the International Organization for Standardization (ISO) (ISO, n.d. a).
2. **The British Standards Institution (BSI).** BSI is a non-profit distributing organization and is the recognized UK National Standards body (ISO, n.d. a). The organisation was granted A Royal Charter in 1929, with the objectives to (1) promote trade by developing common industrial standards; (2) reduce waste – by simplifying production and distribution; and (3) protect the consumer – through the use of licensed marks to identify conformity to standards (ISO, n.d. a). Unlike the ANSI, BSI publishes over 3,100 standards annually. BSI standards are underpinned and developed by a collaborative

approach, engaging with UK industry experts, government bodies, trade associations, businesses of all sizes and consumers (BSI, 2022). The BSI is a non-EEA member of the European Committee for Standardization (CEN) and a full member of the ISO. As a non-EEA member of CEN, BSI has an important vote on the adoption of European Standards but also might have to replace its own standards by European standards.

3. **The International Organization for Standardization (ISO)**. ISO is an independent, non-governmental international organization, with a membership of 165 national standards bodies and is based in Geneva (ISO, n.d. b). International organisations generally rely on ISO standards, including the UN-Institutions and the WTO. Given its importance for trade, the WTO directs its Members to use relevant international standards, such as those developed by ISO and other standard-setting organisations, as the basis for domestic technical regulations as per The Agreement on Technical Barriers to Trade (OECD & ISO, 2016).

In addition, there are various standard setting organisations of great regional importance, including:

1. **The European Committee for Standardisation (CEN).** CEN is one of the three standard bodies recognized by the European Union and brings together the national standardization bodies of 33 European countries. It provides a platform for the development of European standards on various types of products, materials, services, and processes related to topics on air and space, chemicals and construction (European Commission, n.d.). Members include all EU countries, 3 EFTA-countries and a few other countries including the United Kingdom. National standardisation bodies of EU and EFTA countries have the responsibility of developing European consensus. However member countries that are not part of the European Economic Area also have voting rights, proportional to their market share. European Standards which are adopted transpose the national standards of member countries. CEN also has procedures to enable the voluntary cooperation between industry, businesses, public authorities, and other stakeholders (European Commission, n.d.). An important note is that although European Standards transpose national standards, they can be supplemented with non-contradictory and complementary specification at national level.
2. **GOST** refers to a set of technical standards maintained by the Euro-Asian Council for Standardization, Metrology and Certification (EASC), a regional standards organization operating under the auspices of the Commonwealth of Independent States (CIS) formed by post-Soviet republics in Eurasia (Rosstandard, 2020). GOST standards were originally developed by the USSR as part of its national standardization strategy. GOST R is the body recognized by the Russian Federation to be the Federal Executive Body, implementing inter-industry coordination and functional regulating in the fields of standardization, metrology and conformity assessment (ISO, n.d. a).

GOST R and CEN standards are voluntary standards, which can nevertheless contain obligatory requirements (ISO, n.d. a; CEN, 2019).

In most of these standards, industry experts play an important role. This is also the case for standard bodies who rely on the consensus between country representatives such as CEN and

ISO. Countries often nominate experts with strong national industry ties to represent their home country on expert panels/committees. These experts are usually backed by a diverse group of national experts in their home country. These standards organisations have procedures in place to review on a regular basis existing standards. It is important to note that this is not the case for all national standard organizations. This is illustrated by the Indian example on masonry cement where the latest version of the mandatory standards dates back several decades.

Construction

In construction, standards and codes are very important and often prescribe the material to be used. This is particularly true for applications which require medium to coarse sand which tend to come with more restrictive requirements than applications which rely on finer sand. Despite a global drive for homogenisation of standards, no standard institute has yet a global dominance in construction. Instead standards and codes still vary from region to region and are not purely performance based (e.g. BS 1199 and 1200:1976; IS 2116:1980; Broothaers, 2000). In the last decade a growing number of regional and national standards and building/infrastructure codes have started to accommodate alternative sources of sand in response to the changing availability/accessibility of naturally occurring sand resources. Yet in many regions standards or infrastructure codes have not yet been updated. Technical standards which date back to the end of the 20th century are largely tailored to primary materials such as virgin sand and gravel and in certain cases crushed rock (e.g. IS 2116:1980; BS 1199 and 1200:1976). This variation between standards can be illustrated for masonry mortar. Sand used for masonry mortar is of relevance as it is usually considered to be the finest sand for an application with relatively strict construction standards. In construction, sand which is finer than mortar sand is usually used as "fill" or blended with coarser materials. The minimum requirements for the median grain size of masonry sand vary from around 125 μm in Belgium (Broothaers, 2000), 150 μm in India (IS 2116:1980), about 210 μm in the Netherlands and the UK (BS-1199 and BS-1200, Broothaers, 2000), to 300 μm in the United States (ASTM C144-18).

Finally, it is important to note that it is common in infrastructure projects to refer to older outdated standards which restrict the use of new technologies or materials. Updating the standards is thus only the first step in the process, norms, codes and tender documents of infrastructure/construction works need to follow.

Land reclamation and restoration

There are very few standards prescribing what type of material should be used in land reclamation works although these standards are not commonly referred to. The British Standards (BS 6349-5) are one of the very few standards to indicate what sand to use, though only in very general terms. It indicates that well-graded free-draining sand with particle sizes in the range of 100 to 600 μm is the best compromise between a material that is easily pumped in pipes over considerable distances (i.e. finer material) and a material which is easily handled and placed without material excessive losses (coarser material). The material requirements are normally imposed by the client, which is usually the public authority. Material requirements are often partially repeated in successive dredging projects, however are often only known to those tendering for the execution of the project. The management of the material supply, including the identification of sources, is often outsourced to the dredging contractors. Obtaining knowledge on material requirements is often of strategic importance to potential suppliers.

Industrial application

Technical (manufacturing) standards with requirements for industrial sands, including silica sand, are usually not imposed, however there are exceptions e.g. sand for water filtrations. National standards that do exist (e.g. for glass sands) are usually considered by the industry as far too broad to be of practical use (the manufacturer). This is because specifications tend to be mutually agreed between the producer and the user of the sand. For many industrial sand applications, the user has its own recipe and procedure to come to the final product. Once the production line is established, the specifications of the sand are determined for a prolonged period of time in order to avoid further costs to the production line. The lifespan of for example a modern glass melting furnace is often well beyond 15 years. For many industrial sands the supply chain is therefore very short.

6 Sand production, consumption and trade

This section provides a quantitative overview of the (pre-COVID pandemic) sand market, regional trends and trade statistics, and prices. It draws extensively on Friot and Gallagher (2021, 2022).

6.1 Data and information challenges

Although more aggregates are extracted from nature than any other material after water (UNEP, 2014), reliable data on their extraction is only available in certain industrialised countries. Global production of crushed stone, sand and gravel for construction uses is estimated to be around 50 Bt in 2017/2018 (O'Brien, 2019). A proxy-based estimation generated by the United Nations Environment Programme (based on USGS cement statistics) yielded a figure of 45 Bt for 2018 (UNEP, 2019; USGS, 2021). As global annual cement production is expected to increase to 4.83 Bt in 2030, aggregates use could reach beyond 50 Bt per year by 2030 (UNEP, 2014; 2019).

6.2 Regional production trends

Distribution of global aggregates production. Asia leads global aggregates production (65%), driven largely by activities in China (40%) and India (10%). Production in the Americas is estimated to be around 9%, 8% in Africa, 7% in the Middle East and 6% in Europe. According to GAIN, aggregate production per capita ranges from 3 tonnes per capita in China or South Africa, to 14.4 in the United Arab Emirates, with an average of 5.8 in Europe, 7.5 in the USA and 11.4 in Canada (O'Brien, 2019).

Aggregates production drivers. Aggregates production trends vary over time in ways that can be hard to interpret globally because of regional differences. Core drivers include general economic conditions and construction industry investment and economic performance, and, though less important, population growth (Menegaki & Kaliampakos, 2010). For instance, the 2008 economic crisis reduced aggregates production by around 35% in several countries like the USA and India. As such, the current socio-economic situation and expected scenarios for post-COVID public recovery investment in transport, health-related building fabric, energy and other infrastructure construction (e.g. Habiyaremye et al., 2020; Oladimeji et al., 2021; Gozens & Jotzo, 2020) need to be considered carefully in future trends analysis.

How much comes from rivers and coastlines? A wide variety of sand types compounds the uncertainty around how much is extracted from land or water, recycled from existing uses or transformed from other materials at the global level. Quantitative information is available at global, regional and national levels – but not for all countries. Outside Europe, for example, information per type of aggregates can be found for India (40% crushed stone, 30% sand and 30% of gravels) and for the USA (UEPG, n.d.). In Turkey, crushed rocks account for 93% of the production. Marine aggregates account, on average, only for 1.5% but represent up to 19% of the production in the Netherlands and 15% in Iceland. The share of manufactured aggregates is usually less than 3% per country except in Luxembourg (71%). Interestingly, recycled aggregates are estimated at around 8% (or 4.5% in our computations) on average, with a maximum of 26% in France (UEPG, n.d.).

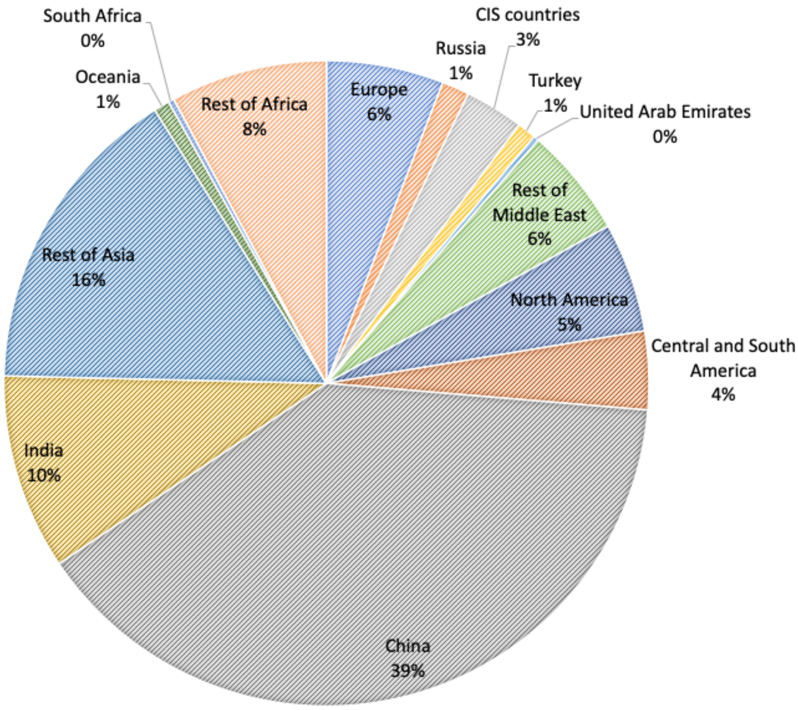

FIGURE 4. ESTIMATES OF GLOBAL AGGREGATES PRODUCTION IN 2017/2018 (50 BT).

Data source: O'Brien, 2019.

6.3 Export and import trends

How much sand is traded globally per year? Global trade in industrial mineral commodities is around 1 billion tonnes per year between 2014 and 2018 (based on UN Comtrade data, harmonized by resourcetrade.earth). The most traded goods are sand and gravel (37% in 2018) as well as cement (19% in 2018, but 45% in 2017). Global trade in sand and gravel, quartz, cement, concrete and ceramics (category code: SGQCC) is increasing at a regular rate with a doubling of the traded mass over the last 20 years, from 318 Mt in 1996 to 620 Mt in 2018 (based on UN Comtrade data, harmonized by the CEPII in the BACI database). Comparing with the current global base estimate of 50 Bt of aggregates consumed globally per year, **traded sand and gravel, quartz, cement, concrete and ceramics** are likely to be equal to about **1% to 2% of the annual global aggregates production.** This rough estimation corresponds with recent research findings by Torres et al. (2021).

Which countries import the largest volumes? The largest importers over the period 1996-2018 cumulatively are Singapore (983 Mt), the USA (915 Mt), the Netherlands (907 Mt), Germany (539 Mt) and Belgium-Luxembourg (498 Mt). It is worth noting that most international trade is regional with the exception of South America which imports more from the rest of the world than what is traded within the region (Friot and Gallagher, 2021).

6.4 Sand consumption data

We know that the construction industry is the largest demand sector for the end-use of ore-sand, but how large is it? The U.S. Geological Survey only estimates global annual end-use for industrial sand and gravel. Looking at three major industrial uses, such as glass manufacturing, electronics and energy production, brings the estimate to **200-300 Mt** used per year. However, this does not include most common (construction) sands, e.g. used for concrete (which is the base data for consumption proxy estimates). At the top end of the range, 300 Mt of sand's end-use in industrial applications amount to **less than 0.5% of estimated annual global aggregates production.** Land reclamation is likely to have an upper bound of 2,000 Mt consumed in this end-use per year, or approximately **4% of total estimated annual global aggregates production. In total, non-construction end-uses likely account for approximately 5% of the estimated annual global aggregates production.** That implies the majority of end-use demand for sand, gravel and crushed rock comes from the construction sector and therefore is more likely to present circular economy opportunities at scale (Friot and Gallagher, 2021).

6.5 Opportunities for circular economy solutions to river & marine sand consumption in the construction sector

Construction products. UEPG (n.d.) suggests that in the European region, concrete products account for 45% of the construction product market, while structural (unbound) materials account for 40% and road asphalt around 10%.

TABLE 2. DISTRIBUTION OF DEMAND FOR AGGREGATES AMONG PRODUCTS IN EUROPE.

PRODUCTS IN EUROPE	%
Structural (unbound) materials	40
Ready mixed concrete	25
Precast concrete	15
Asphalt products	10
Architectural concrete products	5
Armour stone	3
Railway ballast	2

Source: UEPG, extracted from Friot and Gallagher (2022).

Construction products end use. Around 65% of aggregates are used for building developments, 25% for residential buildings and 35% for infrastructure in Europe. This equilibrium between uses is probably representative of a region without strong economic growth and an already mature built environment. The reverse is true in India with 66% of aggregates being used in infrastructure while 34% is used in buildings (15% for residential buildings). Again, this is representative of a rapidly growing economy investing in infrastructure network upgrading and expansion.

TABLE 3. DISTRIBUTION OF DEMAND FOR AGGREGATES AMONG END-USES IN EUROPE & INDIA.

Aggregates end uses	Europe, %	India, %
Residential buildings (single-unit housing, multi-unit apartment buildings)	25	15
Non-residential buildings (commercial buildings, hospitals, schools)	40	19
Non-building uses	35	66
Infrastructure, category 1 (roads, airport runways, railways, waterways)	*n.d.*	*n.d.*
Infrastructure, category 2 (bridges, harbors, offshore pipeline stabilization)	*n.d.*	*n.d.*

Sources: UEPG, GAIN, extracted from Friot and Gallagher (2022).

What proportion of naturally-sourced sand and gravel can be replaced in concrete and construction applications?

Sand is mixed with other materials in standardised volumetric proportions to produce various concrete grades and when used for other construction applications. For example, the UK composition for concrete is generally defined as 1.5% air, 10% cement, 18.5% water, 25% fine aggregate (sand) and 45% coarse aggregate (crushed rock/gravel) by volume. Who are the major private sector entities and what other 'green' concrete alternatives are they currently exploring? This will be one of the important questions to understand and answer when entering the market with a particular ore-sand product.

6.6 Sand prices

Based on industry knowledge, the price of sand in long distance sand trade and infrastructure projects is not determined by the global interplay of supply and demand, even when the material is traded over large distances. In many parts of the world, the available sand resources are considered infinite by authorities. In many of those regions sand extraction without a license or at no administrative cost or tax is tolerated. Therefore the price of sand often reflects the cost to extract it. The capital intensity of sand extraction ranges from very labour intensive to very capital intensive. Marine sand dredging is for example known to be highly capital intensive and wages tend to be a relatively small fraction of their operating cost. A 2013 study by Rabobank shows that the annual capital expenditure of the top 4 European dredging companies is several hundreds of millions, with wages accounting only for 17.8% of the total operating costs. Based on industry knowledge worldwide, a typical dredging project with nearby offshore sand sources can expect to pay around 4-6 euro/m^3 of sand across the world. This equals approximately 2.5 to 3.75 euro/t. Depending on its use this sand needs further processing, e.g. washing. Typical market values drawing on peer reviewed literature are given in Table 4.

On the other hand, artisanal and small-scale mining is very labour intensive with local wages being an important part of the cost. A typical process of artisanal sand mining along the axis of Cotonou-Accra-Lomé is described by Choplin (2020). A 10-wheel truck load (approx. 10 cubic meter) had a value of 18'000-30'000 FCFA (2.7-4.5 Euro/m^3) in the period 2016-2018, if purchased at the site of extraction and 80'000 - 100'000 (12-15 Euro/m^3) when bought right off the truck. In Southeast Asia, small scale miners using hydraulic pumps or small-scale dredging vessels can achieve similarly low values per cubic meter (i.e. 3-5 Euro/m^3) when dredging nearby sandbars in rivers, lacustrine areas or lagunes. In a developed country like the United States, the metric ton value of construction sand from terrestrial sources including glacial deposits, river channels, and river floodplains is estimated at 9.58 USD and 12.19 USD for crushed stone (USGS 2021). Silica sand usually commands higher prices than construction sand. The bulk of the market is however still local with the exception of (very) high purity quartz. Silica sand prices typically range between 10 to 50 euro/t. The value of industrial sand is to an important extent determined by the silica grade. Typical values are provided in Table 5.

Stakeholder interviews have shown that sand prices can increase steeply for areas experiencing local sand shortages. Market proximity of sand sources is often a key determining factor in sand prices, which in turn partly depends on the quality and type of transport infrastructure available (road, rail, navigation channel and marine ports). In our interviews, higher prices were for example observed in Kenya with reported market values for construction sand between 15 and 28 USD per tonne, and in Sierra Leone with values ranging between 25 and 200 USD/t[11]. Prices which are much higher than the extraction cost are also common for marine sand (see Table 4) and river mining as illustrated for São Paulo (15-30 USD/m^3) by Ulsen at al. (2021). Royalties, duties or taxes are generally only a minor fraction of the overall cost. Very few countries currently raise taxes or impose duties to a level which would disincentivize the extraction of naturally occurring sand. There is limited harmonization in how these taxes and duties are raised and at which governance level (national, regional or local; see Bahn et. al 2013 for the European context).

Industry engagement with both the construction and industrial sand extraction industry indicates however a tightening of procedures to obtain a gravel/sand extraction permit in many countries, with a considerable effect on sand prices.

TABLE 4. SAND PRICING FOR MARINE DREDGING PROJECTS.

Country	Lower value (Euro/m^3)	Higher value (Euro/m^3)	Year market value	Source
The Netherlands foreshore	3	4	2013	Jonkman et al. (2013)
The Netherlands beach	3	8	2001 & 2013	Jonkman et al. (2013) & Otten et al. (2002)
Australia	5	5	2009	Linham, Green and Nicholls (2010)

[11] These price values are based on interviews with 21 respondents over this project's reporting report. Further engagement with relevant stakeholders will be necessary to confirm these prices.

France	4	6	2009	-“-
Germany	4	8	2009	-“-
Italy	5	6	2009	-“-
New Zealand	7	54	2009	-“-
South Africa	11	11	2009	-“-
Spain	4	7	2009	-“-
United Kingdom	3	34	2009	-“-
USA California	6	12	2009	-“-
United States	4	16	2015	Aerts et al. (2018)
Vietnam	5.2	5.2	2015	Boos & Dahlstrom (2015)

TABLE 5. SILICA SAND PRICING.

Country or region	Lower value reported (Euro/t)	Higher value reported (Euro/t)	Year market value	Source
General estimate (95%+ silica) and uses of silica sand with a lower percentage of silica which come with additional requirements incl. iron content				
General estimate for the Netherlands	22.5	-	2001	Otten et al. (2002)
Global estimate	20	200	2020	Di Pierro (2021)
USA - sports fields	24	58	2016	USGS (2019), conversion rate 1 Euro = 1.11 USD
USA - Oil & gas	14	60	2016	-“-
USA - filtration	32	89	2016	-“-
USA - foundry	28	86	2016	-“-
Clear glass grade sand (97.5%+) comes with additional requirements incl. iron content				
Global	23	-	2014	Flook R: in Vatalis et al., (2015), conversion rate 1 Euro = 1.33 USD
China - Ceramic applications	34	-	2019	European Commission DG Trade (2019)
USA - Ceramic	37	44	2016	USGS (2019), conversion rate 1 Euro = 1.11 USD
USA - glass making	9	51		-“-
Optical glass grade (99.8%+) comes with additional requirements incl. iron content				
Global	113	-	2014	Flook R in Vatalis et al. (2015), conversion rate 1 Euro = 1.33 USD
High purity quartz (99.95%+), Fe_2O_3 <15ppm, Al_2O_3<300ppm, alkali earth oxides <150ppm				
Global	226	3759	2014	Flook R in Vatalis et al. (2015), conversion rate 1 Euro = 1.33 USD

7 Sampling and material characterisation of Vale sand

This section provides an overview of iron ore mineral processing operations, describes the procedure for obtaining a representative sample, and presents the results from the material characterisation and other tests. The sample originates from Brucutu mine in the state of Minas Gerais, Brazil – Vale's first mine with full-scale sand recovery operations and an environmental license for sand production (obtained in 2020).

7.1 Overview of mineral processing and sand recovery

The typical mineral processing operations for iron ore include ore size reduction via crushing and milling, classification by sieves or cyclones, mineral recovery (concentration) via gravity separation, flotation and/or magnetic separation, and dewatering (filtering). On a particle size basis, there can be four (interconnected) processing streams: coarse (e.g. +8 mm), medium (+1-8 mm), fine (+0.15-1 mm), and very fine (-0.15 mm). These may result in the production of iron ore concentrates in the form of lumps (coarse), sinter feed fines (fine to medium), and pellet feed fines (fine and very fine). The fines products have to undergo an additional agglomeration step, at the plant or elsewhere, such as sintering and pelletizing respectively, resulting in improved mechanical properties as well as a partial change in the chemical content. Iron ore fines products typically have higher iron content and attract a premium price. Brucutu plant produces iron ore concentrates in the form of sinter feed and pellet feed fines (Figure 5).

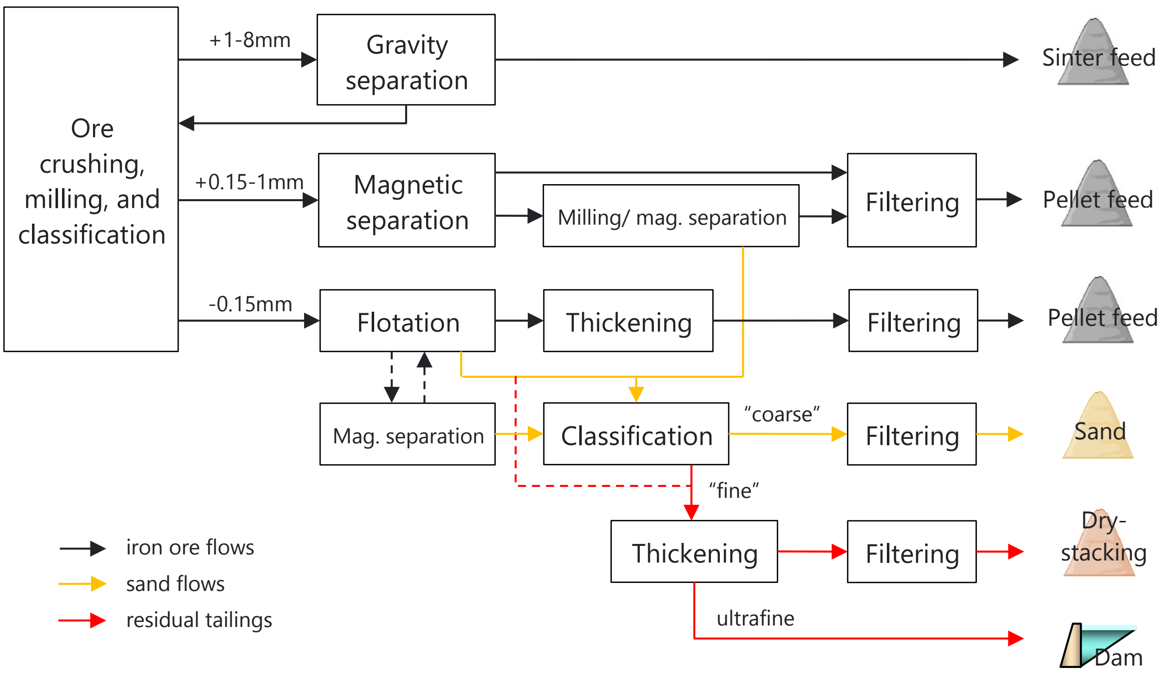

FIGURE 5. SCHEMATIC OF IRON ORE PRODUCTION AND ORE-SAND RECOVERY AT BRUCUTU.

Note: simplified, based on the information provided by Vale. Black coloured arrows represent iron ore flows, yellow – by-product sand, and red – residual tailings.

All major processing steps can directly contribute to the co-recovery of sand. Compared with the rejection of all remaining components in the ore as tailings, additional steps to recover ore-sand may include segregation and/or separate handling of silica-rich components, classification by cyclones, filtering, etc. At Brucutu, the coarser streams of reject materials from magnetic separation and flotation undergo additional classification and water reduction with the use of hydrocyclones, this is followed by dewatering on the filter belt and then discharged into an open-air storage via a conveyor belt. Depending on the type of processed ore(s), specific mineral processing steps/routes, weather conditions and other factors, the physical parameters, chemical content, and visual appearance of the sand by-product(s) may slightly vary.

7.2 Material sampling and delivery

The research team developed a protocol for independent sampling of ore-sand from Vale's iron processing plants, based on BS EN 932-1:1997 ("Tests for general properties of aggregates. Methods for sampling"). The protocol was intended for the specific sampling point, namely the conveyor belt, prior to the material being discharged into an open-air storage. The procedures were discussed with relevant personnel at the processing plant, followed by the sampling team, and witnessed and verified by an independent observer from the research team present at the time of sampling (Prof Douglas Mazzinghy from Federal University of Minas Gerais).

The aim of sampling was to obtain a representative sand material that can be further analysed and tested for the use in construction related applications. The sampling was done on the 28th of July 2021 at the Brucutu iron ore processing plant. The weather conditions at the time of sampling were sunny and dry (27°C). Two batches of samples were taken – one in the morning and another in the afternoon – in order to assess the variability of the material. Additional historical data of the material composition was also provided by Vale for verification purposes.

The collected samples, about 400 kg net, were shipped to The University of Queensland, Australia, for testing and analysis. Two control subsamples (~2 kg each) were also taken, with one being sent separately to The University of Queensland, while another was used for the quick material characterization at Federal University of Minas Gerais. The photographic evidence was also taken at the time of sampling and upon delivery of the material (Figure 6 and Figure 7).

FIGURE 6. INDEPENDENT SAMPLING AT BRUCUTU PROCESSING PLANT.

Notes: dewatering filter belt, conveyor belt before and after sampling, and sampling team.

FIGURE 7. TRANSPORTATION AND DELIVERY OF VALE SAND SAMPLE.

Notes: plastic barrels on the pallets ready for transportation, and an oven-dry sample.

7.3 Physical and chemical tests

Upon arrival to The University of Queensland, all received individually packaged samples (34 plastic bags in total) were tested for particle size distribution to confirm two distinct batches, from the morning (VS-1) and afternoon sampling (VS-2). All further tests were done on the samples separately, unless indicated otherwise.

The particle size distribution (of two batches) was analysed through sieving and a hydrometer test (AS1289.3.6.2/ AS1289.3.6.3; providing data on the weight basis), as well as using fully automated laser diffraction method (volumetric basis). Due to significant differences in iron oxides and quartz content across different particle size ranges, as confirmed by further tests, the volumetric and weight-based results are not fully comparable. It was also found that the measurement of the -2 μm fraction with the use of hydrometer test is not valid for this type of material due to very high content of iron oxides in the fines. The conventional testing by hydrometer (without prior removal of iron oxides) indicated 1.3-2 wt.% of clay size particles content, while the laser diffraction method reporting zero, and the mineral liberation analysis (based on automated microscopy) returning a result of 0.01 wt.%.

Both samples can be characterised as a silty very fine sand, with D_v10 at 60 (56) μm, D_v50 – 134 (132) μm, and D_v90 – 271 (284) μm, and a dmf (average for nine points from D_v10 to D_v90) at 130 (145) μm. The content of fines (particle size below 75 μm) is 22.2 (21.0) wt.%, which is higher than the generally recommended maximum level of 15-20% for manufactured sands. However, on the volumetric basis, the content of fines is slightly lower (17 vol.% and 19 vol.% respectively).

The results from physical and chemical tests confirm the material being compliant with general requirements for construction applications, apart from the fines content. The material has near neutral pH (6.9-7.3); very low electrical conductivity (20 μS/cm; as paste); and extremely low soluble sulphates and chlorides content (<10 mg/kg). It has typical average bulk density for silty sands (1440 kg/m^3), and specific gravity typical for sand with a presence of iron oxides (2.79). The level of total carbon and total organic carbon is very low (<0.02%).

The sample is mainly represented by silica (89.7-90.8%) and iron oxides (8.6-9.7%), with low alumina content (0.2%), and minor concentrations of other major oxides. All trace elements are present in very minor concentrations (e.g. Cr 10 ppm, Pb 2-3 ppm, and As 1.5 ppm) which is significantly below environmental thresholds and average levels for most soils. The chemical content analysis on a size-by-size basis shows that most residual iron oxides and other impurities are present in the very fine fraction (-63 µm, which accounts for ~18 wt. % of the sample) and coarser fraction (+300 µm; ~8 wt.%). The lowest iron oxides (~2%) and the highest silica content (97-98%) were identified for the +100-200 µm fraction (~40 wt.%).

The mineralogy of the sample was characterised on the basis of mineral liberation analysis and petrographic observations. The results confirm that the material is mainly represented by quartz (90-91%), different iron oxides (8-9%), but mainly hematite and goethite, minor kaolinite (0.2%), and very minor (<0.1%) chlorite, pyrolusite, sericite, diaspore and feldspar. The particles shape can be characterised as very angular.

Due to very low concentrations of heavy metals and other elements of concern, there is minimal risk for any contaminated seepage. A conventional leaching procedure such as TCLP (Toxicity Characteristic Leaching Procedure), with the focus on metals, was selected for testing. TCLP simulates what happens when a sample is disposed in an urban landfill condition, and to determine whether the material is safe according to current guidelines. The TCLP results confirm that the material is non-toxic, with most metals being undetected (i.e. below detection limits), and only minor concentration of zinc being reported in the leachate (Table 6).

TABLE 6. PHYSICAL AND CHEMICAL TESTS RESULTS.

Parameter	Unit	VS-1	VS-2	Notes
Less than 2µm	vol. %	0.0	0.0	No clay size particles detected
Clay and silt (<75µm)	vol. %	17.0	19.0	This is lower than weight-based result
Clay and silt (<75µm)	wt. %	22.2	21.0	The maximum recommended for manufactured sands is up to 15-20%
Specific gravity	g/cm3	2.79	2.79	Quartz (2.65); sand with iron (2.75-3); normal weight sands (2.1-3.2)
Bulk density	kg/m3	1430	1450	Normal sands (1300-1700); silty sands (1100-1600)
pH 1:5 (soils)	pH unit	7.3	6.9	Neutral, suitable for most applications
pH saturated paste	pH unit	8.8	8.6	Slightly alkaline, mostly acceptable
Electrical conductivity (EC) (paste)	µS/cm	21	20	Indirectly indicates low level of soluble salts (i.e. 21:1000*0.34 ≈ 0.007%)
Soluble sulphates	mg/kg	<10	<10	Suitable for most applications
Soluble chlorides	mg/kg	<10	<10	Suitable for most applications
Total carbon (TC)	%	<0.02	<0.02	Suitable for most applications
Moisture content	%	12.1	9.3	Typically expected in the range 2-6%
Plasticity index	%	0	0	Non-plastic (e.g. no clay minerals)
TCLP test results:				
As,Cd,Cr,Cu,Pb,Ni,Hg	mg/L	BDL	BDL	All metals are below detection limits
Zn	mg/L	0.2	0.5	Below the recommended limit for drinking water quality (e.g. 5 mg/L)

7.4 Particle shape and texture

The particles shape and texture can significantly affect the applicability and performance of fine aggregates in different applications, in particular the workability and strength of concrete. Based on the shape, the particles can be generally subdivided into rounded, irregular, angular and flaky, while surface texture can be classified as glassy, smooth, granular, crystalline, porous and honeycomb (Gambhir, 2013). Different methods and indexes can be used to assess and describe the shape and texture characteristics, however currently there is no uniform approach. Some of the examples include angularity number, elongation index, and flakiness index.

Generally, the use of angular aggregates allows to achieve a higher compressive strength of concrete, rounded particles require lesser amount of water and cement for the same workability, while the per cent of flaky (and elongated) particles has to be restricted. Aggregates with a rough porous texture are preferred to a smooth surface, significantly increasing cement-aggregates bond (Gambhir, 2013).

For the analysis of shape and texture, the results from automated mineral liberation analysis (MLA) were used. MLA combines backscattered electron (BSE) images with an energy dispersive X-ray system (EDX) for elemental analysis, and a computer software to match and identify minerals and map their distribution. In addition, it routinely collects other quantitative and qualitative data including grain size distribution and particle shape parameters such as aspect ratio, shape factor and angularity. The benefits of MLA include its high productivity, statistical representation (many thousands of particles), as well as an ability to analyse very fine material (Pszonka and Sala, 2018). It also allows to filter and search through the data set of particles/grains by different parameters of interest, and supports the export of data to other applications.

Based on the results from MLA and additional calculations, the average sphericity was estimated at 0.37, while average roundness at 0.66. This would typically place Vale sand somewhere in between manufactured sands and naturally-sourced sands. While these results require a more detailed further investigation, including verification and comparison with other sand types, the findings may point to a unique feature of ore-sands in terms of the particle shape, and thus lead to a potential niche that they can cover in different applications.

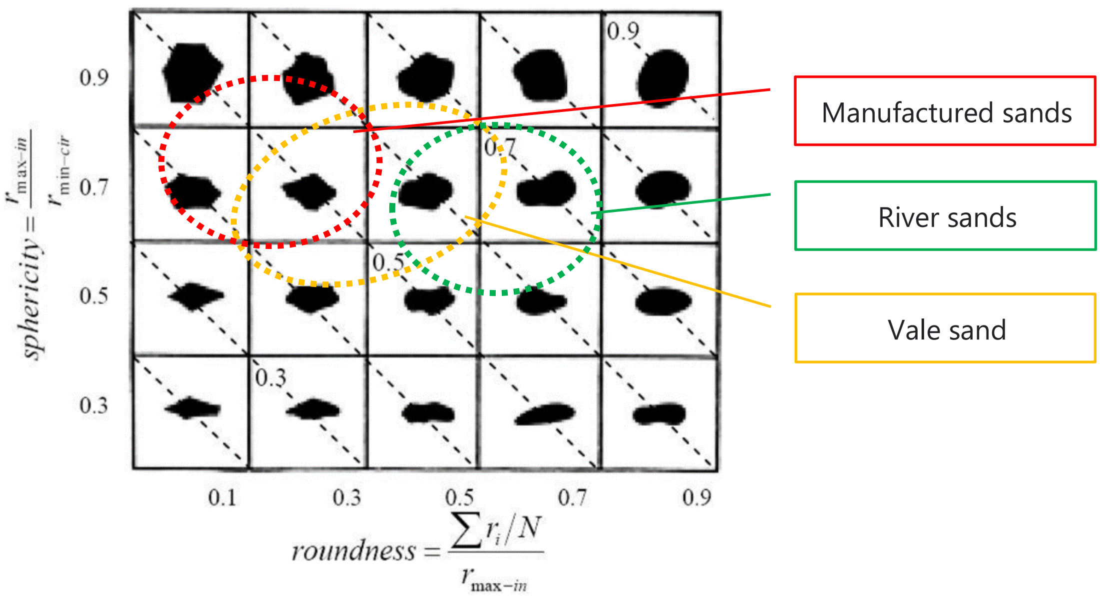

FIGURE 8. THE FRAMEWORK AND ANALYSIS OF PARTICLE SHAPE PARAMETERS.

Notes: the parameters and fit area for Vale sand are estimated on the basis of MLA data (+100-300 µm fraction). An explanation of the model can be also found in (Shen et al., 2016).

7.5 Shear strength

Higher shear strength may be required in order to provide more safety and stability for structures, in particular for aggregates used as a road base, construction fill, and in land reclamation. Essentially, shear strength arises from friction and resistance between particles, significantly affected by grading, mineralogy, and particles shape and texture.

The direct shear test to measure the failure stresses of Vale sand, based on AS 1289.6.2.2-2020, was performed at the Laboratory of Geomechanics, UQ's School of Civil Engineering. Prior to the test, distilled water was added to the sample (50:50 mixture of VS-1 and VS-2) to achieve 5% moisture content, then loaded into a 100 mm x 100 mm shear box and compacted to a relative density of 35% (i.e. ~1543 kg/m^3). Three normal stresses of 100, 200 and 400 kPa were applied in each series of the test, at the same shearing rate increase of 1 mm/min.

The maximum shear stress for each normal stress applied were 88.7, 171.3 and 327.3 kPa at failure respectively. The effective stress friction angle of sand (φ) was 61.8° (Figure 9).

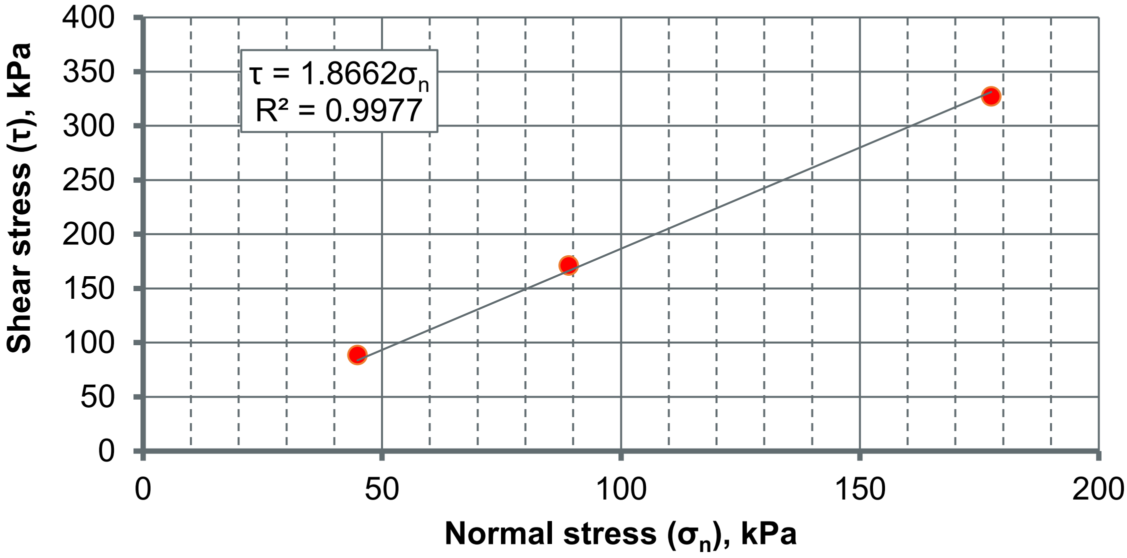

FIGURE 9. SHEAR STRESS WITH VARIOUS LEVELS OF NORMAL STRESS.

The results from applying different levels of normal stress are presented in Figure 10. Significantly higher shear stress was achieved under the loads of 200 and 400 kPa, indicating high level of interlocking and resistance between the particles when the material is more compacted.

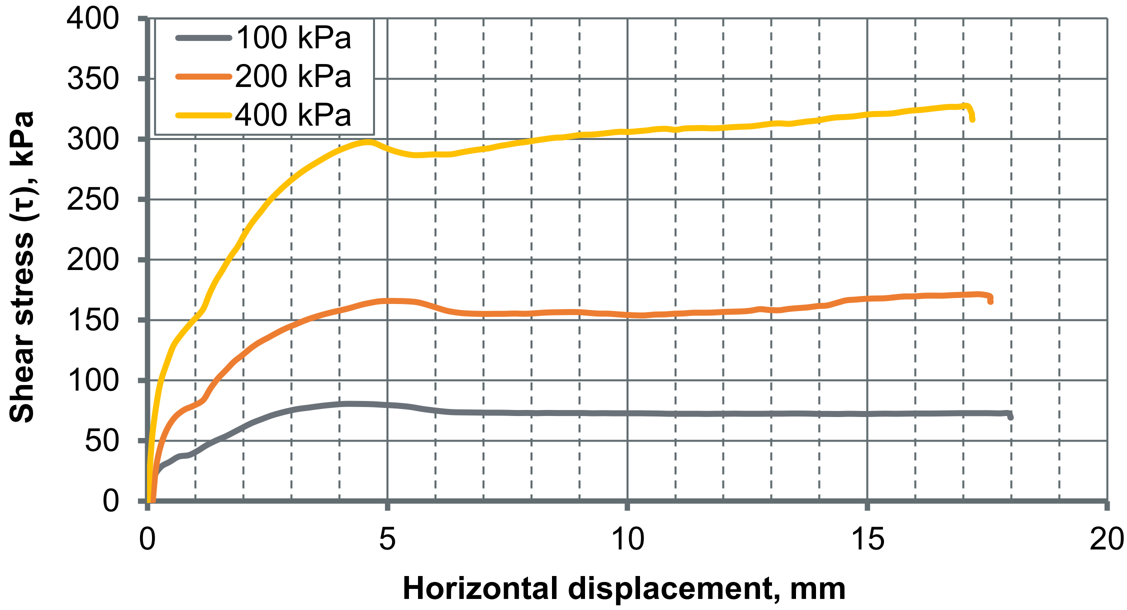

FIGURE 10. SHEAR STRESS – HORIZONTAL DISPLACEMENT UNDER DIFFERENT LEVELS OF NORMAL STRESS.

7.6 Options to enhance the properties of ore-sand for industrial use

The sample is characterised as a silty very fine sand. This may limit its application for concreting (major sand use in construction), unless blended with coarser materials. However, there are several known industrial applications for fine (silica) sand. Considering the relatively high silica content and very low level of trace elements in the sample, additional test work was implemented to test the opportunities for minimizing the residual iron oxides content and potentially meeting the chemical requirements for silica sand, e.g. in glass manufacturing.

The magnetic separation trial was done on the Frantz Magnetic Barrier Laboratory Separator (Model LB-1), at the Sample Preparation Laboratory, of The University of Queensland's School of Earth and Environmental Sciences. Three size fractions were selected for the test: +200-300 µm, +300-450 µm and +450 µm (washed and oven-dried). The final non-magnetic products (silica sand) were additionally washed with ultrapure water (to remove residual coating on the grains) and oven-dried before being submitted for analysis.

The silica sand products accounted for 74.2, 73.6 and 47.2 wt. % of the initial input materials respectively. The concentration of residual iron oxides varied from 0.2 to 0.08 wt.%, while silica was in the range of 99.5-99.7 wt.%. Overall, the coarser fractions showed better results for both the recovery of silica sand as well as residual iron oxides.

FIGURE 11. FINAL SILICA SAND PRODUCTS AFTER EXPERIMENTAL TRIALS.

Notes: +200-300 µm, +300-450 µm and +450 µm size fractions respectively.

TABLE 7. CHEMICAL CONTENT ANALYSIS OF SAMPLES BEFORE AND AFTER EXPERIMENTAL TRIALS.

Analyte	+200-300 µm fraction		+300 µm fractions		Silica sand specs*	
	Original	After trials	Original	After trials	Coloured container glass	Clear flat glass
SiO_2	96.5	99.7	71.6	99.5-99.7	97.0	99.0
Fe_2O_3	3.3	0.2	26.6	0.08-0.1	0.25	0.10
Al_2O_3	0.09	0.01	0.47	<0.01	0.1	0.5

*Notes: All data is presented as weight per cent. Tungsten carbide grinding media was used for preparing samples for XRF analysis. *BS2975:1988 (superseded) Methods for sampling and analysis of glass-making sands.*

The gravity-based separation trial was done on the laboratory scale Wilfley table, at the Sample Preparation Laboratory, of The University of Queensland's School of Earth and Environmental Sciences. The original unsized material as well as separated -63 µm fraction were used for the test. In both cases, there was an observed recovery of iron oxides into the heavier fraction. However, the overall recovery and product grade (i.e. iron oxides content) was much higher when treating the -63 µm fraction. After a single test run, without any optimization, the iron oxides content in the product (heavier fraction) was increased from 36.1 to 80.1 wt.%, while silica decreased from 62.4 to 19.4 wt.%. This demonstrates a potential for additional recovery of iron ore (either within or outside exiting processing circuits), also contributing to lowering the content of fines in the sand by-product.

7.7 Summary of findings

The collected sample of Vale sand – a by-product from iron ore processing – can be characterised as a very angular silty (very) fine sand, mainly composed of silica (89.7-90.8%) and residual iron oxides (8.6-9.7%). From a particle size distribution point of view, the material has higher fines content (-75 µm fraction; 21-22 wt.%) than recommended for manufactured sands in most countries (0-20 wt.%), and thus would require additional testing for specific applications. Although, on the volumetric basis the content of fines is lower (17-19 vol.%), due to much higher iron oxides content in the fines. The material characterisation results indicate that the material is inert and non-toxic, and can be suitable for certain applications, either on its own or as a part of a blend (e.g. with coarser sand, in order to meet specific grading requirements). In the case of regulatory limits on the use of manufactured and recycled sands, a blending with naturally-sourced sand may be required unless an exemption for ore-sands is made.

A set of durability tests in this work has been limited to the shear test, therefore additional work will be required to confirm specific properties for the use in construction applications. The measured shear strength indicate that Vale sand may be suitable for the use as a fill material in land reclamation and infrastructure works, as it demonstrates great interlocking and resistance between the particles, especially when the material is compacted. This will be also a subject to meeting other requirements such as grading, compatibility with the hosting eco-system, etc.

The test work to enhance the properties of the preliminary sample included magnetic and gravity-based separation trials. The results indicate some opportunities for minimizing residual iron and increasing silica content. A significant improvement and potential for producing silica sand has been demonstrated, achieving 99.5-99.7% silica and 0.1% iron oxides content in the final products. This may potentially allow meeting the requirements for silica sand used in different industrial applications. Importantly, the level of other impurities in the original and processed materials is very low and within the specifications for silica sand. A full-scale test work is beyond the scope of this project, but further investigation is recommended.

8 Safeguarding sustainable and just transitions

There are several factors that could contribute to or jeopardise the potential to scale-up the recovery of ore-sands and their introduction to the markets. This section includes: an overview of mine tailings (direct) reuse and its limitations, in comparison with ore-sands; potential contaminants in sand recovered from different mineral ores and other associated risks; possible changes in the management of (residual) tailings; and the potential to impact or displace existing sand producers from the introduction of ore-sands.

8.1 Limitations of mine tailings (direct) reuse

The reuse of mine waste as alternative construction materials has been known for a long time. To date, however, most examples at scale refer to the reuse of wastes as alternatives to crushed rock and gravel size materials, mainly for road construction, and not sand (for example the Mittersill tungsten mine in Austria, and the Mt Carbine tungsten mine and Nagambie gold mines in Australia). Typically, uneconomic ores and overburden materials are rejected earlier in the process, and relatively benign suitable waste rock can be easily identified and stockpiled separately for potential reuse.

Unlike waste rock, tailings are mainly the result of mineral processing of economic ores, and thus their physical, chemical and mineralogical properties as potential sand materials can be modified during processing. Most existing examples refer to the reuse of tailings without any pre- or reprocessing to achieve the required properties of sand, e.g. for concreting applications. At best, the individual size fractions have been reused as coarse and fine aggregates (Huang et al., 2013; Kuranchie et al., 2015). This often results in an inferior and inconsistent quality, limiting their reuse to non-structural applications and/or to the form of diluting of or blending with conventional materials.

Specifically, there are many examples where tailings – e.g. from gold, copper, and iron ore mining – successfully substituted from 10% to 40% of naturally-sourced sand in concrete in small-scale experiments and trials (Kumar et al., 2014; Reddy et al., 2016; Swetha et al., 2015; Ugama et al., 2014; Ugama & Ejeh, 2014; Zhao et al., 2014). Full replacement often results in a decrease in compressive and flexural strength performance, mainly associated with the excess of fines but also other factors. The cases where a full replacement achieved comparable or better results are very rare, lack supporting evidence, and often can be simply explained by a poor research design, e.g. comparing the use of well graded tailings versus poorly graded natural sand (Che et al., 2019; Kuranchie et al., 2015; Pavez et al., 2016).

Some studies reported the role of fines (in tailings) as a filler. The addition of a small quantity of fines did not compromise plasticity, while promoted a 'filler effect', optimizing internal pore structure, reducing voids and contributing to a better mechanical response (Cui et al., 2021; Fontes et al., 2016; Protasio et al., 2021; Zhao et al., 2021). At the same time, many studies used plasticisers to improve the workability and maintain the water-to-cement ratio when adding tailings to concrete mixtures. The addition of plasticiser can help mitigate both – high content of fines as well as angularity and rougher texture of tailings particles, if compared with river sand (Che et al., 2019; Chinnappa & Karra, 2020; Filho et al., 2017; Huang et al., 2013; Protasio et al., 2021; Reddy et al., 2016; Shettima et al., 2016; Tian et al., 2016; Zhang et al., 2020).

The examples of other additives include fly ash, silica fume, BF slag, and reinforcement fibres. Some of these additives help to reduce porosity in concrete, such as fly ash (Tian et al., 2016), and contribute to a better compressive strength, e.g. fibres (Huang et al., 2013). The presence of iron oxides can also contribute to accelerated hydration, improving compressive strength (Coner, 1990 apud Yellishetty et al., 2008).

There are also examples where tailings partially replaced cement, contributing to the cementitious properties of the mix (Onuaguluchi & Eren, 2013). However, most often, cementitious properties relate to the reuse of ground slag and not tailings, e.g. copper slag, attributed to the presence of pozzolanic materials and CaO (Pavez et al., 2018; Shi et al., 2008). Nevertheless, an investigation from Kundu et al. (2016) used copper tailings with a good response for 10% replacement of cement by tailings. Most likely, a combination of several factors combined to achieve such result, e.g. densification of the microstructure, reduction in capillary porosity, and minor pozzolanic properties (Tixier et al., 1997).

Higher density of tailings materials often increases the density of the final products. Typically, a greater amount of iron oxides is responsible for the increased density, due to much higher specific gravity (e.g. 5.2 for magnetite versus 2.65 for quartz). Higher density can compromise the load capacity in some applications, meaning limiting the reuse options to non-structural applications (Okeyinka et al., 2015). In particular, for a higher per cent of use or full replacement, non-structural applications such as pavements can be more suitable for tailings (Ismail & AL-Hashmi, 2008). Although, Zhang et al. (2020) reported that with the right amount of iron ore tailings in the mix, concrete can present a higher packing density reducing acid penetration and improving compressive strength.

Most studies on the direct reuse of iron ore tailings indicate the absence of hazardous impurities in these materials, however the reuse of other types of tailings can pose challenges. In particular, copper tailings and slags often contain heavy metals and other elements in concentrations that may pose serious hazards to the environment (Kundu et al., 2016). This again may limit their (direct) reuse entirely or to blending and/or lower-end applications.

Many examples of tailings and other mine waste reuse can be also found at the mine site level, especially when there is a lack of suitable local construction materials. These include road base materials, walls and embankments construction, e.g. for the waste storage facilities, infill and backfill materials (including as cemented backfill) for underground and open-cut mines, reuse in landscaping and rehabilitation of mined areas and/or waste storage facilities. In most cases, however, similar limitations to those mentioned above would apply. Moreover, when reused at the mine site, the quality of these materials does not need to fully comply with the strict requirements used in civil construction, environmental regulation for urban development, agricultural and recreational land use, etc.

8.2 Potential contaminants in ore-sand

As distinct from the direct use of tailings, ore-sand offers the possibility of taking advantage of the physical processing (e.g. crushing and grinding) of the material that is already undertaken for the primary ore and adding additional mineral processing circuits (e.g. separation) to obtain characteristics suitable for a sand product. This process has the potential to remove or reduce contaminants. Nevertheless, the presence of potential contaminants is an issue of utmost concern depending on the geological composition of the ore.

The specifications for sand can be highly variable depending on the area and type of application, and due to differences between regional and national standards, norms, and guidelines. In most cases, however, (construction) sand has to be free of contaminants such as metal sulphides, alkalis, salts, coal, shale, certain clay and mica minerals or other materials in such form and/or in such quantities that can adversely affect its physical characteristics, chemical properties and/or appearance in different applications. In some cases, although relatively rare, there may be also concerns for the presence of radioactive elements at concentrations significantly higher than the background level in the area.

Potential impurities in sand recovered from mineral ores and options to avoid those can significantly vary from one mine site to another. In most cases, a detailed understanding of the processing flowsheet and material flows would be required for finding feasible solutions. Some impurities can be already concentrated and recovered as a part of the existing mineral processing and/or waste management operations. A separate handling of those streams and sometimes additional treatment may be needed to achieve the required properties of (construction) aggregate materials.

Sulphide minerals

Sulphide minerals, when in contact with oxygen and/or water, and accelerated by iron- and sulphur-oxidising bacteria, can break down to form secondary minerals. In concrete, this can lead to the expansion and cracking, e.g. via sulphide erosion and internal sulphate attack processes, often causing structures to fail (Campos et al., 2018; Dong et al., 2019). In other applications, this may also result in acid and metalliferous drainage (AMD) – a well-known major global environmental issue in managing mine waste. Sulphide ores are the dominant source for base metals, such as copper, lead, zinc, nickel, as well as for gold and silver. This is in contrast to primarily oxide ores for iron, aluminium, chromium, manganese, magnesium, and titanium (Reuter et al., 2005). A small amount of pyrite (iron sulphide, the most abundant sulphide mineral) can be present in some naturally sourced sands, however, its reactivity is typically lower compared to freshly mined and processed materials. Pyrite concentrate itself is a traded commodity (often more valuable than sand), mainly used in the production of sulphuric acid. In the absence of a market for pyrite and/or its low quality, mining companies may choose to desulphurise tailings materials before disposal in order to drastically decrease the risks of AMD. The desulphurised materials can then be used in mined land rehabilitation as well as serve as precursors for ore-sand.

Clay and mica minerals

Certain minerals with a sheet or layered structure can significantly expand when wet and shrink when dry. This effect can be detrimental to concreting applications, often leading to cracking and structural damage over time. These include clays and mica, although some forms are less detrimental than others. In addition, in fresh concrete, surface coating by clays may interfere with the bonding between particles, while mica, due to a flaky structure, may affect the workability and strength of concrete (Rathor et al, 2020). Where sand is used as fill or as part of a foundation, the presence of mica and clays could reduce the sand body's resistance to shear failure, potentially leading to consolidation over time and infrastructure damage. Interestingly, some applications of sand may accept and/or even require a certain per cent of clay, e.g. bricky sand for the use in mortar where clay can partially substitute cementitious materials. Different minerals and forms of clay and mica are also locally and globally traded commodities. The major applications for clays include brick-making, floor and wall tiles, lightweight aggregates, cement (including low carbon cements), ceramics, absorbents, drilling "muds", paints, and agriculture. Different forms of mica are used in paints, thermal and electrical insulation, drilling "muds", as well as extender and filler in gypsum wallboards, plastics and rubber.

Salts and alkalis

Salt-related damage may have both a chemical and physical nature, e.g. leading to efflorescence and corrosion, and can affect building and transportation structures in a significant way (Delgado et al, 2016). It is important to avoid or minimize the content of soluble salts in sand, e.g. chlorides and sulphates, which in most cases can be removed by washing with fresh water.

Concrete and masonries can suffer from a specific chemical degradation – alkali-silica reactions, also known as "concrete cancer". The latter occurs between alkalis present in cement and/or aggregates (mainly sodium and potassium) and reactive forms of silica, when present in particular proportion and fineness, typically over a period of many years. The reactive and potentially reactive forms of silica, such as amorphous and microcrystalline silica, are known to occur in different rock types, including siliceous limestones, certain sandstones, chalcedonic cherts, etc. A similar detrimental effect can be observed from alkali-carbonate reactions, occurring between alkalis and certain carbonate minerals (Rathor et al., 2020). Additional tests can be required to confirm alkali-silica reactivity potential, e.g. accelerated mortar bar test (ASTM C1567-21). There are also different methods to control and/or prevent alkali-silica reactions, e.g. by adding fly ash and/or using low-alkali cement (Gambhir, 2013).

Coal and shale

The presence of coal, lignite (brown coal), shale and other low-density particles in aggregates may lead to pitting and scaling, significantly affecting the compressive strength of concrete (Rathor et al., 2020). Apart from fossil fuels deposits, significant amounts of coal and shale can be also found in other sedimentary rocks, including those used for metal extraction.

Heavy metals and toxic elements

Different metals and metalloids can be toxic to humans and the environment, when present in certain quantities and forms in soil, water or air dust. These have to be controlled in the aggregate materials, including assessing their leachability if present in significant quantities. Depending on the type of application, specific requirements and testing procedures may vary. The examples of the most toxic elements include Pb, Cr VI, Cd, As, Se, and Hg.

Certain heavy metals and their compounds, e.g. lead and zinc, are also known as retarders of the cement hydration process. Their release into the pore solution of fresh concrete can inhibit hydration, decreasing the mechanical properties of concrete (Keppert et al., 2018; Matejka et al., 2021).

Radioactive elements and minerals

Some deposits may contain significant amounts of naturally occurring radioactive elements (mainly thorium and uranium), especially in the case of polymetallic ores (e.g. iron ore-copper-gold-uranium and rare earths deposits) and some heavy mineral sands (e.g. used for the recovery of titanium, zirconium, and tin). The mineral association and distribution of radioactive elements in the processed materials can significantly vary and needs to be assessed on the case-by-case basis.

8.3 Management of residual tailings

Any changes in mining methods and/or mineral processing operations may affect the volume and types of mine waste generated, requiring adjustments in the waste management practices. The recovery of ore-sand may result in the decrease of residual tailings, but also change their composition and physicochemical properties, e.g. by increasing the proportion of fines and/or concentration of toxic elements. This may affect the most appropriate tailings storage facility type and/or deposition method, water recovery operations, rehabilitation approach, long-term risks, and post closure land use options. These changes can lead to positive outcomes from an environmental and economic point of view in some cases, while in others – not.

However, ideally, the recovery of ore-sand would minimize the amount of residual waste, in particular tailings, such that it can more easily be incorporated into the existing land management, backfilling and/or mined land rehabilitation operations. Essentially, this could avoid the need for a permanent waste storage facility or resulting in a short-lived waste only.

Mine waste management practices continue to evolve, and so do the regulatory requirements and community expectations. Some of the best current practices include dry stacking, backfilling (including in-pit disposal), desulphurisation, progressive rehabilitation, and/or a combination of those. Stockpiling for future reprocessing or reuse can be also a viable option in some cases.

Dry stacking of (residual) tailings

Highly dewatered or filtered tailings can be used for dry stacking, allowing to avoid conventional (wet) tailings dams and significantly reducing the risk of catastrophic failures (Franks et al., 2021). This also leads to a reduced water use; lower footprint from waste storage enabling progressive rehabilitation; reduced risk of groundwater contamination through seepage; and in some cases easier regulatory approval for the mine and/or its waste storage facilities (Roche et al., 2017). This, however, often results in higher capital and operational costs, and requires additional measures to prevent wind and water erosion.

The particle size distribution and physicochemical properties are very important factors in dry staking. The recovery of coarser fraction into ore-sand may result in residual tailings becoming much finer and thus less suitable.[12] The recovery of relatively benign materials may also increase

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[12] At the same time there are innovations in coarse particle flotation (discussed further below) that could lead to the availability of coarser ore-sands and residual tails that would avoid such a problem.

the concentration of hazardous elements in the waste for disposal, likely increasing the risks of AMD unless countermeasures are in place.

Using (residual) tailings as a backfill material

The use of tailings (and other mine waste) in backfilling of previously mined areas allows to significantly reduce surface storage area and may provide additional benefits (Roche et al., 2017). Depending on the type of backfilling, additional operations and costs may include thickening, pumping, and addition of a binder (e.g. cement) and other additives. The recovery of ore-sand (fraction) may affect backfilling operations similarly to dry stacking, in particular affecting the particle size distribution, and in some cases workability and water-to-cement ratio.

Tailings desulphurisation

The desulphurisation of tailings refers to different processes that can be used to separate sulphide minerals from mine tailings before disposal (Golev et al., 2017). Ideally, this allows to produce non-reactive (benign) tailings with significantly reduced risks of AMD. These techniques can be used throughout the life of mine but especially relevant in the last few years in preparation for mined land rehabilitation, providing on-site cover materials (Bussière, 2007). The (smaller) sulphide-rich fraction can be further upgraded and used for metal recovery and/or sulphuric acid production, otherwise managed separately or backfilled in underground mines.

There may be opportunities for incorporating or combining the recovery of ore-sand with desulphurisation operations, allowing to improve the overall outcomes. In this case, it is important to consider and overview the life of mine perspective, accounting for and balancing between the use of the (benign) sand-like materials at the mine site, e.g. backfilling and mined land rehabilitation, versus selling them off at the market.

Progressive rehabilitation

Some mining companies choose to rehabilitate “as they go”, which means backfilling and revegetation of the mine areas that are exhausted while mining works move to other areas (ICMM, 2019). Implementing progressive rehabilitation provides the opportunity to reduce the total disturbance (and environmental liability) at any given time, often also reducing the amount of the financial provision required for the company. The types of activities that can be implemented as progressive rehabilitation are controlled by site-specific conditions and mine plan. In some cases, the line between mining and rehabilitation may blur, e.g. (underground) backfilling and in-pit mine waste disposal.

Some of the most common progressive rehabilitation works include:

- strategic placement of uneconomic and subeconomic materials;
- segregation and capping or encapsulation of problematic waste materials;
- diversion of unimpacted waters;
- stabilisation works;
- cover placement;
- soil management; and
- revegetation.

The recovered ore-sand materials and components can be incorporated in some of the activities above, and in some cases are required at the site rather than available for markets. This is especially relevant towards the end of mine operations and/or at the increased rate of rehabilitation works at the site.

8.4 Displacing or sustaining other sand mining practices?

Sand is overwhelmingly a locally consumed resource. Dictated by the economics of transportation, locally extracted sand on the most part services local markets, providing the material foundation for domestic development. Sand is thus principally extracted by large numbers of small- and medium-sized domestic enterprises who rely on sand for their livelihoods, and in the developing world, are often in circumstances of poverty. Millions of people mine sand in thousands of places, with impacts accumulating at local, regional, national, continental and global scales. It is critical, therefore, to bring people along on the journey toward resolving sand sustainability challenge while introducing alternative aggregates.

Any transformation in sand governance must recognise the diversity of settings in which sand is extracted and be guided by those voices most closely involved and influenced by sand extraction, whether it be the miners who may rely on sand for their livelihoods, the businesses who receive the benefit of sand's utility, or the local communities who are dependent on the presence of sand in ecosystems for healthy waterways and clean drinking water. Involving these actors in decision-making, and the design and implementation of any programs or policies is essential for mobilising a successful coalition. Participatory approaches are necessary at all scales, including at national and global levels where decisions are often dominated by expert viewpoints.

Inclusivity is also important in the language that we use. In much of the written literature on sand and sustainability the only reference to the large number of – often informal – sand and aggregate miners in the developing world is as criminals, using pejorative and stigmatising terms such as 'illegal sand mining' and 'sand mafia'. In reality, sand mining is a livelihood diversification activity for large numbers of people in poverty. There are significant barriers to artisanal and small-scale miners to obtain legal licenses, and in some countries, sand is excluded from the formal definition of 'minerals' in the mining act leaving no opportunity to mine 'legally'. The loose application of the term sand 'mafia' implies that informal sand miners are in positions of power, which is counter to the actual situation in many settings. This is not to say that sand mining actors will welcome change. There are many actors and businesses within the sand supply chain that are not motivated by livelihood concerns, and instead operate to maximise economic benefit. There are also many circumstances where miners, informal and formal, large and small-scale, have extracted without concern for the environmental and social consequences, have resisted calls for change, or have used power, and even violence, to entrench the status quo. However, the generalisation of examples where sand mining is linked with criminal activities or criminal networks to represent the global situation is counterproductive to the sustainable development outcome being sought and reverts back to an earlier time where the analysis of environmental issues was divorced from the human development implications.

Whether ore-sand is sustainable depends on whether its producers have the knowledge and skills to introduce their sand while delivering improved social and environmental outcomes for local communities, including artisanal and small-scale mining (ASM) and those on the receiving end of impacts. In those locations where ore-sand can become a part of the supply, we can understand the consequences and trade-offs of its introduction by engaging with local sand stakeholders, in particular ASM sand producers. This engagement will give us a better understanding of when and how ore-sand can contribute positively to ASM sand livelihoods, communities and the environment. Franks et al. (2020) make a compelling case for 'place-based perspectives' in decision-making, agenda setting and action in the sand sector. They call for inclusive action that considers the views and interests of those most affected to ensure not only just transitions amid technology shifts, but also decision-making that reflects the localised nature of sand. This aligns with the intent of the Mosi-oa-Tunya Declaration on Artisanal and Small-scale Mining, Quarrying and Development (2018) which called for ASM miners to be "at the heart of any efforts to transform ASM", and for recognition of the vital role of development minerals like sand in local livelihoods (Franks et al., 2020).

A myriad of questions emerge when considering the social, economic and environmental changes that the arrival of ore-sand can trigger locally and in relation to ASM. One might ask, and find different answers according to the locality: What is the current size of the local sand market? How is it expected to evolve in the next years, decade or decades? Who are the local ASM sand producers? Note that we do not refer to the 'key' producers – no ASM livelihood or livelihood contribution is too small that it can be discarded. What are other sources of sand locally? What tangible livelihood alternatives do ASM sand producers have and what are their environmental effects? What development and skills needs and potential do ASM sand producers have? How organised are ASM sand producers? What are their rights locally, nationally and internationally? How can ore-sand benefit these ASM sand producers? What are the environmental and social effects of current sand extraction practices and market dynamics? How do these shift when seen through an intergenerational equity lens? Where can improvement happen and how can it benefit the most vulnerable?

By exploring the above questions collaborative with sand stakeholders, in particular ASM producers, it is possible to define criteria on what makes ore-sand sustainable and protocols to build a socially and environmentally sustainable role for the product locally. Criteria might relate to the nature, distribution and size of ASM sand operations and output, and appropriate levels of ore-sand participation; or to what a just transition for ASM sand producers means specifically. Protocols could outline ways to identify mutually beneficial business models where producers of ore-sands contribute to ASM sand livelihoods. Similarly, the protocols can provide guidance on how to engage with ASM sand producers to explore mutually beneficial solutions that are good for the environment, and what kinds of local governance structures might be necessary.

9 Life cycle assessment

This section provides the results from the life cycle assessment (LCA) of ore-sand derived from iron ore mining operations, based on the example of Vale sand.

9.1 Introduction

Sustainability assessments broadly can help support decision-making and policy in a context of comprehensive accounting for diverse impacts from environmental, economic, and social dimensions, transcending a purely technical/scientific evaluation. Stakeholder interviews indicate that ideally a sustainability assessment should be done on a case-by-case basis, considering all three dimensions of sustainability for current sand extraction or production activities and for locally available alternatives. Each dimension requires a specific evaluation since a systematic and harmonized approach is still lacking.

In crossing the chasm to larger-scale uptake, a sustainability assessment will require taking into account both the environmental implications (i.e. ecosystem impacts) and the socio-economic implications of switching to this alternative material. The sustainability assessment field is large and methodologies are diverse. Several valuable frameworks are available that could complement an environmental assessment of ore-sand in the future. Relevant sustainability assessment frameworks which could be tailored to ore-sand and complement a LCA in the future include a Just Transitions lens and/or a Strategic Environmental Assessment.

In this section, we focus exclusively on the environmental side of sustainability, based on the life cycle assessment, considering a single way towards sustainability, namely substitution. Importantly, we remind readers that substitution is only one of the possible options towards environmental sustainability. Reducing demand for sand is another obvious option (e.g. by increasing the usage of existing products and/or extending their lifetime). Typical examples include using office space for additional activities during the night-time, increasing the density of dwellings or re-purposing existing buildings rather than demolishing and building new ones. While the potential impact of such solutions is probably larger than technical solutions, they require changes in practices and values which are difficult to evaluate and beyond the current study's scope.

The objective of this life cycle assessment is to evaluate the environmental impacts of ore-sand in a quantitative way when possible, and in a qualitative way otherwise. The key factors driving environmental impacts are identified to maximize the potential of ore-sand and guide future actions. In this section, the environmental impacts of the production of ore-sand are also compared to the impacts of natural sand (river sand, sand from open-pits and marine sand) and of manufactured sand. The potential of ore-sand in terms of reduction of greenhouse gas emissions is then discussed. Finally, the limits of the proposed approach, current knowledge and data are discussed, with recommendations for future research.

9.2 Methodology

The environmental sustainability of ore-sand is evaluated with the help of a quantitative method commonly applied to quantify the environmental impacts of products and services. This approach, supported by UN Environment, is called Life Cycle Assessment (LCA).[13]

Life Cycle Assessment

The LCA approach quantifies the potential environmental impacts of human activities by considering the whole life cycle of an activity, i.e. its production, use and end-of-life as well as all contributing activities. Multiple indicators are generated to present as complete picture as possible, considering impacts related to climate change, ecosystem quality, human health and resource use. LCA is mainly used to (a) generate environmental profiles of technologies, products, and companies, (b) identify improvement opportunities, (c) support decision-making, and (d) provide information for marketing and communication.

An LCA is a standardized approach that uses modelling, formalized in the ISO 14040 standard (ISO 14040:2006), covering both the evaluation and the communication of results. LCA is based on conventions and each choice taken in the process can have large consequences: transparency about the approach, data and assumptions are thus key elements to enable a critical review of the results.

Life Cycle Assessment of Vale sand

This study is a screening (i.e. simplified, not full LCA) attributional[14] LCA of ore-sand production at the Brucutu mine, using data and explanations provided by Vale as well as secondary data from the literature. Results are computed[15] with the Ecoinvent database (Wernet et al., 2016), one of the most used and trusted LCA database globally (currently in version 3.8.1). The comparison of the results with alternatives is performed against results from the literature and information from Ecoinvent.

Three indicators are considered: firstly, climate change, expressed in kg of CO_2-equivalent, and computed according to the IPCC 2013 approach, considering a 100-year global warming potential. The second indicator is potential damage to human health, considering human toxicity (carcinogenic and non-carcinogenic effects), respiratory effects (inorganics and organics), ionizing radiation, and ozone layer depletion, expressed in DALY (Disability Adjusted Life Years) and then normalised. Finally, the third indicator considered is damage to ecosystem quality, considering eco-toxicity, terrestrial acidification and nutrification, as well as land occupation, expressed in PDF·m^2·year/kg emitted (the Potentially Disappeared Fraction over a

[13] More details are available at the Life Cycle Initiative website: https://www.lifecycleinitiative.org/.

[14] According to Finnveden et al. (2009), "attributional LCA describes the environmentally relevant flows to and from a life cycle and its sub-systems, while a consequential LCA describes how environmental relevant flows will change in response to possible decisions".

[15] The applied system model is called 'Allocation, cut-off by classification'. According to the Ecoinvent website: "In this system model, wastes are the producer's responsibility ('polluter pays'), and there is an incentivization to use recyclable products, that are available burden free (cut-off)" (Ecoinvent Association, 2021).

certain area and during a certain time per kg of emitted substance) and then normalised. Damages to human health and to ecosystem quality are computed applying the Life Cycle Impact Assessment (LCIA) method "Impact 2002+" (Jolliet et al., 2003).

Results are not detailed and documented enough to enable public product disclosure of the environmental performance of Vale sand compared to existing products. To avoid any potential legal issue, such claims should be based on a detailed Life Cycle Assessment (LCA) conforming to the ISO 14'040 standard, which is beyond this study's scope in this reporting period.

9.3 Description of the case-study

Ore-sand has the potential to substitute natural sand in various sand-containing products. Producing ore-sand requires however changing current practices in iron ore mining to generate several co-products (iron ore and ore-sand). The implications for this LCA are described in this section.

Substitution-potential of ore-sand

According to Vale, ore-sand from Brucutu can substitute natural sand in several sand-containing products, including fine aggregates for civil construction (concrete, bricks, road layers and rail) and high purity silica. Based on current studies and test applications by Vale, ore-sand seems to be able to substitute natural sand in concrete and bricks, and provides the exact same product characteristics in terms of user needs and experience, maintenance needs and duration. Waste management at the end-of-life is also expected to be strictly similar. As a result, this LCA[16] only considers activities from the extraction of raw materials and energy consumed until the delivery of ore-sand, i.e. to the end-user that will incorporate sand into one of the above-mentioned product.

A material substitution which does not influence the characteristics of a product is a strong assumption, one with potentially large influence for this LCA's results. The following five examples are provided to illustrate its potential implications. Firstly, concrete producers often prefer coarse river sand over its finer alternative as it usually requires less cement, hence less carbon emissions. Secondly, considering a different lifespan for the sand-containing product would potentially imply additional maintenance (hence additional impacts from materials, transportation, etc.) or earlier need for replacement, hence a need for additional sand. Thirdly, considering the necessity for blending with additional materials to ensure physical characteristics of the sand-containing product would reduce the potential advantages provided by ore-sand in the final product or even counteract the possible gains if the complementary material has an impact larger than natural sand (for example, by blending ore-sand with a specific type of manufactured sand). Fourthly, a slight difference in colour (the preliminary sample of ore-sand demonstrated a slight red colour) could imply the need for additional

[16] This LCA is thus effectively a cradle-to-gate study.

measures and/or travel distances to meet demand. Finally, in some cases, the presence of potential contaminants in ore-sand, such as heavy metals, may result in additional releases during the lifetime of the product and/or require additional treatment at its end of life.

Allocation rules for co-products

At the Brucutu mine, the original production process had one major product output (iron ore concentrates), while silica-rich materials were part of the waste stream, ending up as part of wet tailings. Currently, the production of ore-sand requires an additional stage for dewatering (using cyclones) and filtering (using filter-belts), as well as transporting to the storage area. More recently, Vale also started exploring dry stacking as an alternative to wet tailings, a process that reduces the quantity of water in tailings, and that can be combined with the possibility to extract ore-sand. This new process should be set up by 2023.

Various rules can be applied when performing the LCA of a production process with multiple co-products (Allacker et al., 2017). Ore-sand can thus be considered in different ways. First, ore-sand can be considered as a by-product of iron ore processing or by-product from the waste management system since it has limited economic value. In this approach, waste can be considered burden-free, i.e. the environmental impact of iron ore production and tailings management are not to be considered. In this classic way of conceptualising recycled products with low price from waste treatment in open-loop systems (i.e. where the recycled material is used outside of the system generating the waste), the only steps to consider are the waste's collection and the treatment steps to transform it into a usable material.

A second possible approach is to consider ore-sand as a valuable co-product. This approach can be considered if ore-sand production is developed at industrial scale, assuming it is an integral part of the entire production process, and has an added economic value[17] that justifies its co-production. In this case, the impacts of the whole life cycle of iron ore extraction and ore-sand production and waste management are computed. Then, impacts are allocated to the two co-products based on a meaningful parameter (usually the price or weight, unless there is a direct relationship between some parts of the production system and one of the co-products).

It can be understood from the above description that the environmental impacts of ore-sand will differ according to the selected perspective, as it is always the case with multi-output production processes. It can also be understood that the situation can vary according to the situation and evolve over time.

System boundaries

The definition of the system boundaries sets the limits of the life cycle. All activities relevant to the achievement of the objectives of the studied system, as well as all processes and flows having a significant contribution to the potential environmental impacts should be included.

[17] The drivers for ore-sand production currently include its market value, local and global environmental impacts reduction, risk management and land-use avoidance from tailings disposal.

In this study, two different system boundaries are considered (Figure 12). In the case of ore-sand as a by-product of waste management, the only production steps considered are the treatment steps to transform it into a usable material (waste collection is not considered since the transformation occurs in the same facility using the same infrastructure). In the case of ore-sand as a co-product, all mining and processing activities are considered, along with the waste management activities. In both cases, the boundaries go up to the point of sale, which means that transportation from Brucutu is considered as well. Two scenarios are considered for the delivery: by diesel train up to 500 km (MRS and EFVM terminals) and by road (trucks), up to a 200 km radius around Brucutu.

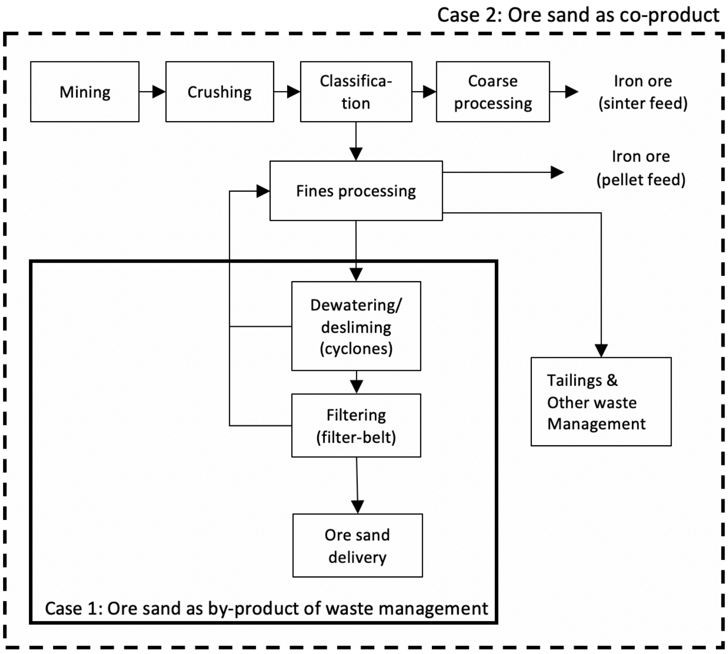

FIGURE 12. SYSTEM BOUNDARIES OF THE LCA OF VALE SAND.

9.4 Results and discussion

A high-quality comparison of the environmental impacts of ore-sand, natural sand and other alternatives is currently not feasible for a multiplicity of reasons. This includes the lack of adequate data on the impacts of the extraction of naturally-sourced sand from rivers and marine environments, and the lack of adequate data on tailings management in the LCA literature (refer to the critical review section below for a detailed description of the issues). This section therefore presents the results that could be generated based on existing knowledge and data. While absolute results might evolve in the future, the discussion about the main drivers of the environmental impacts and the potential benefits of ore-sand should remain valid.

GHG emissions of Vale sand

Ore-sand as a by-product of waste management and as co-product of iron ore mining

The GHG emissions from the production (i.e. not considering delivery) of Vale sand considered as a by-product of waste management are estimated to be 0.6 g of CO_2-equivalent per kg of Vale sand in the case of the Brucutu mine[18].

In the case of dry stacking rather than wet tailings, the results could be slightly different since dewatering and filtering could be part of the necessary steps for dry stacking. As a result, ore-sand would be a by-product of waste management without additional processing or treatment steps. The emissions of ore-sand production (i.e. not considering delivery) could thus be considered close to null.

Considering Vale sand as a co-product of iron ore mining and assuming (a) an industrial scale production of the sand, as well as (b) a market for all the sand produced at the mine, the allocation of the emissions to the two co-products of iron ore mining[19] (iron ore and Vale sand), based on their annual market value, would result in a share of 0.4% of the impacts to ore-sand. This equates to the emissions of 0.5 g of CO_2-equivalent per kg of ore-sand.

The estimates generated with both approaches are very close. As a first estimate, we therefore evaluate the GHG emission of the production of ore-sand to be 0.6 g of CO_2-equivalent per kg of ore-sand since the economic rationales for ore-sand production are not clear.

Comparison with other types of sand

The GHG emissions from ore-sand production (without transportation) are put in perspective in Figure 13, with the average emissions from river sand (4.7 g of CO_2-equivalent per kg of sand) and sand from open-pit mines in Brazil (7.0 g of CO_2-equivalent per kg of sand), taken from the

[18] Two estimations are performed to generate a preliminary guess for the emissions. A lower bound for the emissions is first computed by considering that the additional energy consumption from treatment steps is equivalent to the electricity used for iron ore crushing and screening as provided in (Norgate and Haque, 2010): 2.5 kWh per tonne of ore hence per tonne of sand. Using the average electricity mix in Brazil (220 g of CO_2-eq. per kWh) results in emissions of 0.55 g of CO_2-eq. per kg of ore-sand. An upper-bound is then evaluated by considering half of the emissions computed in (Norgate and Haque, 2010) for iron crushing and screening: 1.25 g of CO_2-eq. per kg of iron ore hence per kg of ore-sand. This is like assuming that half of the electricity is produced with low-efficiency diesel generators (in the original study) and is thus not representative of the Brucutu mine. Knowing that the electricity use for the treatment steps of ore-sand is lower than for crushing and screening, the lower bound is selected.

[19] This evaluation is based on the value provided in Ferreira and Garcia Praça Leite (2015) - 13.32 kg of CO_2-equivalent per tonne of iron ore. They evaluated the impacts of iron ore mining within the iron triangle in Brazil. This value is smaller than the values provided in Ecoinvent for mines in Canada (20.5 kg of CO_2-eq. per tonne of iron ore) and India 23.8 kg of CO_2-eq. per tonne of iron ore). This value is however slightly larger than the estimate provided by Vale: 10.3 kg of CO_2-eq. per tonne of iron ore (personal communication with Vale). A relative price of iron ore to sand of 27 has been selected (USD 160 for iron ore and USD 6 for sand – average prices for Vale in 2021). The proportion of sand to iron ore is estimated to be 1:10 (60% iron ore, 40% tailings among which 15% is ore-sand). This results in emissions of 0.5 g of CO_2-eq. per kg of ore-sand. For comparison, selecting a price ratio of 5 (USD 100 to USD 20) would imply a higher allocation of emissions to ore-sand, hence 2.6 g of CO_2-eq. per kg of ore-sand.

Ecoinvent database, as well as with marine sand from dredging[20] in the UK (6.4 g of CO_2-equivalent per kg of sand) (Aumônier et al., 2010) and manufactured sand (5.26 g of CO_2-equivalent per kg of sand) based on our own computations.

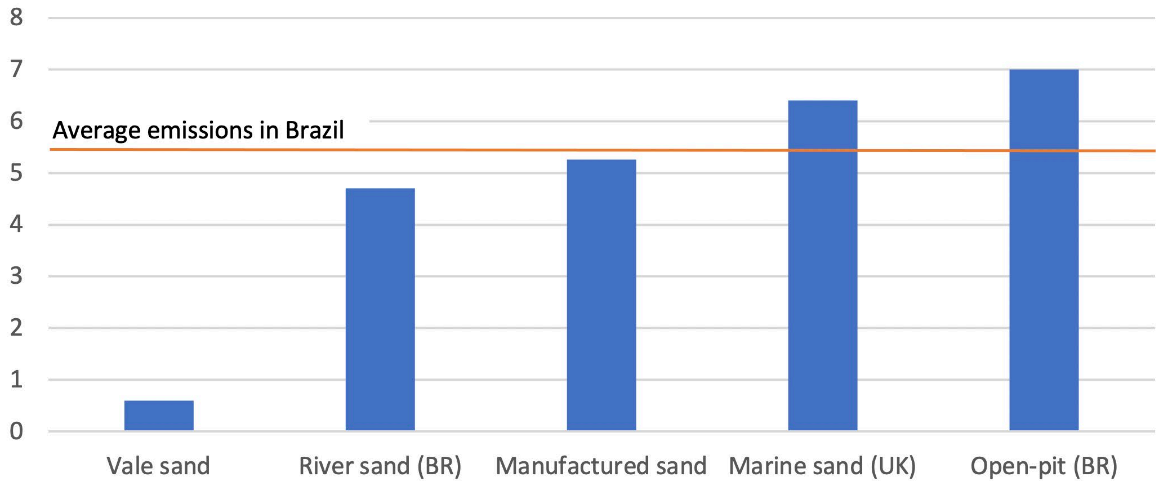

FIGURE 13. GHG EMISSIONS FROM SAND EXTRACTION (IN G OF CO_2-EQUIVALENT PER KG OF SAND).

Note: average emissions for sand extraction in Brazil are estimated as a volume-weighted average between river sand and extraction from open-pits, excluding ore-sand.

Using the estimates for river sand and sand from open-pit mines in Brazil, it is possible to estimate an average 5.4 g of CO_2-equivalent per kg of sand in Brazil. [21] Based on the LCA of river sand extraction from Ecoinvent, it is also possible to extrapolate that artisanal river sand extraction could have ten times lower emissions (hence lower than the 0.5 g of CO_2-equivalent per kg of sand).[22]

We have not been able to identify an existing LCA of manufactured sand within peer-reviewed literature. The value has therefore been computed by combining information[23] on the production of crushed stones from large stone blocks quarries with the additional electricity[24] required by a vertical shaft impact crusher for crushing granite particles as provided in (Fang et

[20] It should be noted that the provided value does not include the release of carbon from seabed bottom trawling. Refer to Sala et al. (2021) for more information on this aspect.

[21] According to the documentation of the Ecoinvent database (referring to a communication with the "Ministério de Minas e Energia" of Brazil in 2009), mining of sand from riverbed deposits represented 70% of Brazilian production of sand for construction, while the other 30% was extracted from open-pit mines.

[22] The LCA considers most of the activities from dredging of slurry to sand in storage piles at the loading port, including separation of slurry (but not sorting of sand by grain size) and washing, and shows that more than 90% of the GHG emissions are from burning diesel.

[23] According to Ecoinvent, crushed rock production in Brazil emits 5 g of CO_2-equivalent per kg of crushed rock.

[24] Fang et al. (2018) report electricity consumption of 0.8-1.6 kWh per tonne of 13-18 mm particle size sand. We assume here an average value of 1.2 kWh per tonne of sand.

al., 2018). Given that close to 98% of the emissions of crushers over their life cycle are induced by electricity use[25] (Landfield and Karra, 2000), only electricity was considered in this study. For manufactured sand, most of the emissions are thus induced by the production of crushed stones, and only 5% by the crushing of these stones into sand.

Based on this data selection (driven by data availability), we conclude that with respect to GHG, emissions induced by sand extraction can range from 0.6 g to 7.0 g of CO_2-equivalent per kg of sand, with ore-sand at the lower end of this range.

For comparison, the GHG emissions from silica sand are between 25 g and 36 g of CO_2-equivalent per kg. Given that silica sand is dried, emissions are higher than for other types of sand.

The important role played by electricity

According to Ferreira and Leite (2015), electricity use during the processing of iron ore in Brazil is responsible for a third of the GHG emissions of iron ore production, considering both mining (dismantling, loading and transportation of ore and waste) and processing (crushing, classification, milling and separation into concentrate and tailings). This is larger than the emissions induced by the mining process itself.

Focusing on GHG emissions only, the environmental performance of ore-sand is thus partly influenced by the choices of energy sources. The average regional GHG emissions from electricity production in Brazil are shown in grams of CO_2-equivalent per kWh in Figure 14. These emissions consider local production and exchanges between regions, as well as trade between countries. Emissions range from 143.4 g to 401 g of CO_2-equivalent per kWh. The GHG emissions induced by ore-sand production in Brazil will thus vary according to regions, potentially up to a factor of 3.

In comparison, the production of a purely hydraulic electricity emits around 10 g of CO_2-equivalent per kWh, an electricity production using photovoltaic panels around 70 g per kWh, while for electricity produced from diesel, this number is at a high 800 g per kWh. For comparison, an average European electricity mix emits around 394 g of CO_2-equivalent per kWh. The regional network CEMIG, providing electricity at Brucutu mine, reports 75 g of CO_2-equivalent per kWh, in the lower range for Brazil.

[25] Considering the US average electricity mix composed at 59% of fossil fuels.

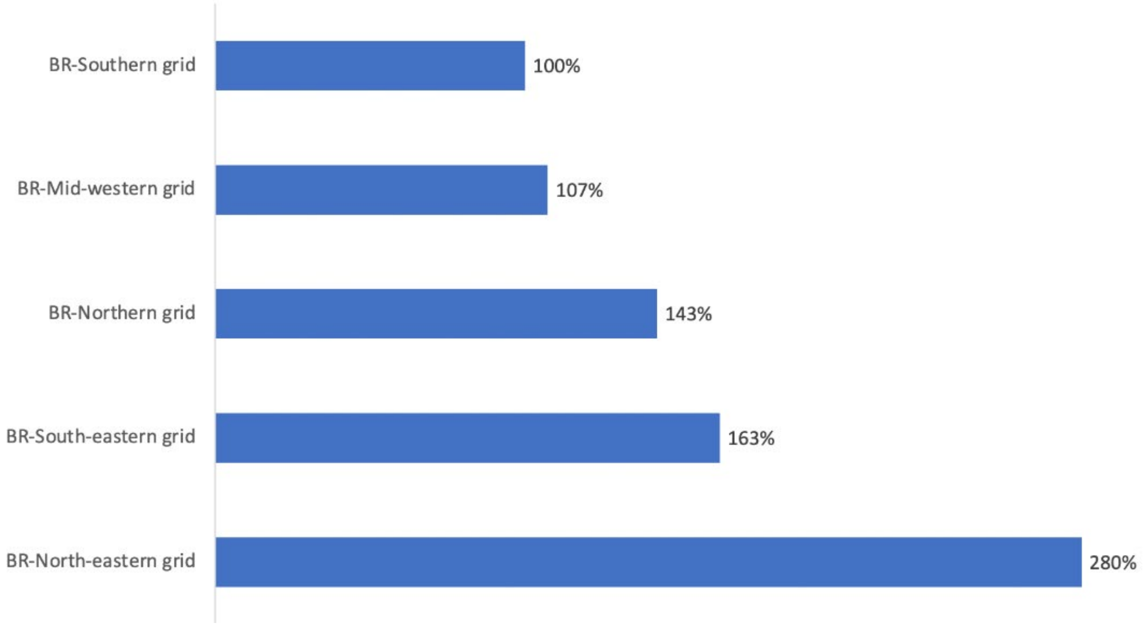

FIGURE 14. GHG EMISSIONS PER KWH OF ELECTRICITY IN BRAZIL.

Note: 100% = 143.5 g of CO_2-equivalent per kWh (BR-Southern grid). Source: Ecoinvent 3.8.

Emissions from ore-sand delivery are larger than the emissions from production

Emissions from ore-sand delivery are larger than the emissions from production (estimated at 0.6 g of CO_2-equivalent per kg of ore-sand). Considering delivery to the sale point in addition to production, GHG emissions from the production and delivery of ore-sand are thus going up and vary between 17.4 (32-tonnes truck transported over 200 km) and 26.3 g of CO_2-equivalent per kg of ore-sand (diesel train transportation over 500 km) in the case of the Brucutu plant. The truck scenario is here better because of the shorter distance (30% less emissions) than the diesel train scenario. Going from diesel trains to electric trains would however change the conclusion since the emissions would be, in this case, around five times lower.

Due to economic feasibility, the maximum distance to market for sand is typically estimated to be no more than 100 km by truck, although 50 km is a preferred range (based on stakeholder interviews). As Figure 15 demonstrates, GHG emissions for this distance are lower when using trains (electric or diesel) than trucks. For a 100 km, they are equivalent to 5.2 g/13.2 g of CO_2-equivalent (diesel train/truck 16-32 t), thus up to 2.4 times larger for truck transportation than the average emissions induced by sand production in Brazil (while they are similar to production when transported by train).

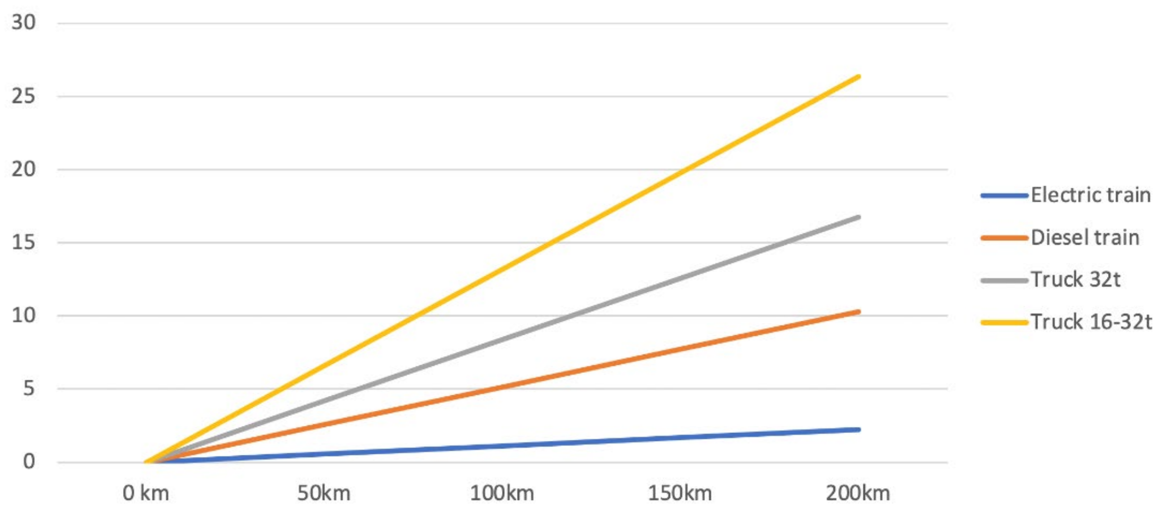

FIGURE 15. GHG EMISSIONS FROM TRANSPORTATION IN BRAZIL (IN G OF CO_2-EQUIVALENT PER KG OF FREIGHT).

Selecting the right transportation mode and the right distance to markets will thus be critical for ore-sand to be competitive with natural sand in terms of GHG emissions.

Delivery is indeed a key factor for the impact across sand types. For example, for river sand, emissions from transportation become larger than the emissions from production as soon as the delivery distance with a small truck is larger than 35 km. In addition to distance, the type of delivery vehicle plays a key role. Smaller and/or unregulated trucks consume more energy per tonne of freight moved than larger and regulated trucks (up to 50% more emissions in Brazil when assessing transportation using average emission factors). Loading rates are also a key aspect since underloaded trucks will not consume much less than well loaded ones, and thus emit proportionally more per transported tonne of ore-sand. The use of recent, regulated and optimally loaded trucks can thus play a key role in reducing the potential GHG emissions of ore-sand.

Sand is also sometimes shipped for longer distances. Assuming the technical and economic feasibility of transporting ore-sand across long-distances, what would be the impact of freight transportation by bulk carrier. For the trip from the EFVM terminal of Vitoria to Singapore (around 9000 nautical miles or 16700 km), emissions would be around 100 g of CO_2-equivalent per kg of freight. Thus, emissions from transporting ore-sand over this distance would be about 200 times higher than emissions from its production.

Other environmental impacts of ore-sand

While climate change (driven by GHG emissions) is the dominant environmental issue today, additional impacts must be considered when evaluating potential alternatives to current practices. This step is needed to avoid a transfer of one impact to the other (e.g. selecting a solution with lower GHG emissions at the cost of higher biodiversity losses).

Several impacts could be considered, even though there is no universal rule for selecting them. The current practice is to complement GHG emissions with indicators related to human health and biodiversity/ecosystem quality. Human health can be impacted, for example, through the emissions of inhalable organic and inorganic substances that might be carcinogenic. Biodiversity and ecosystems can be impacted, for example, through acidification, eutrophication, ecotoxicity or land changes.

In this study, damages to human health and to ecosystem quality from ore-sand (as a by-product of waste management) are induced by electricity production. They will vary strongly depending on the underlying sources of energy, and are thus not discussed here. When considering the case of ore-sand as a co-product of iron-ore mining, the impacts induced by the whole iron ore production process are considered. Ferreira and Garcia Praça Leite (2015) identify that close to half of the damage to human health from iron ore production are caused by particulate matter (2.5-10 microns), a quarter of these impacts by fine particles (<2.5 microns) and another quarter mainly by cadmium and arsenic in water. Ecosystem quality is mainly affected by chromium emissions in the air, as well as by land use (Ibid).

A comparison of the damage caused to human health and ecosystem quality by Vale sand, river sand and sand from open pits in Brazil is shown in Figure 16. To quantify the importance of transportation, the impacts of average sand in Brazil including a delivery within a 200 km distance by truck (16-32 t) are also shown. Vale sand's impact as a co-product is extrapolated from impacts of iron ore production in India (from the Ecoinvent database) since information on iron production in Brazil is not available.

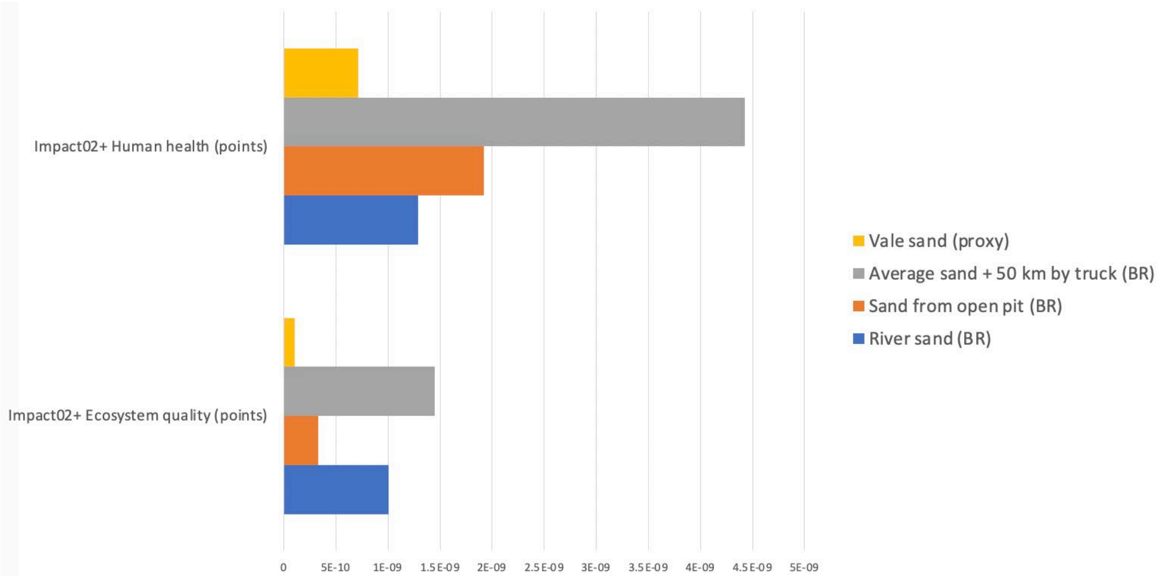

FIGURE 16. IMPACTS ON HUMAN HEALTH AND ECOSYSTEM QUALITY PER KG OF SAND (IMPACT 2002+, IN POINTS).

Due to the inherent uncertainty of the applied Life Cycle Impact Assessment (LCIA) methodologies, it is not possible to identify any meaningful difference between the three types of sand and the results should be considered as similar. However, the available data does not consider the consequences of river (or marine) sand extraction on the physical characteristics of river environments. These impacts are however among the key sustainability issues that have led to a global mobilisation to improve the environmental governance of sand. An adequate quantitative evaluation of these aspects from an LCA perspective is however still lacking. This is a clear limitation of the current assessment because these impacts are perceived to be one of the key differentiators (as well as GHG emissions), between Vale sand and natural sand.

Using available data, we can however infer that transportation by truck has, similarly to GHG emissions, a large impact compared to the production of all sand types, particularly when considering human health induced damages. To reduce damages on human health, particularly in densely populated areas, using relatively newer vehicles is thus particularly important due to their filtering of fine particulates emissions. Tellingly, emissions of fine particulates (PM2.5) are 50% higher for euro3 trucks compared to euro6 trucks (taking 7.5-17 tonnes trucks as example).

Moving beyond this current analysis is challenging. This would require more specific data, both on the local environment of Brucutu and population distribution. Additional information would also be needed on tailings management (wet tailings and dry stacking) for which current LCA evaluations are very generic. Further analysis would also require a better understanding and measures of the changes induced by river or marine sand production to the physical characteristics of the river basin or marine environments. In technical terms, the Life Cycle Inventories of river and marine sand production are incomplete, and their impacts difficult to evaluate.

Five types of impacts of river sand mining can be documented and quantified: changes in (i) bed forms, (ii) sediment characteristics, (iii) water quality and (iv) quantity and (v) biological environment (Padmalal and Maya, 2014). Among these, given current Life Cycle Impact Assessment (LCIA) methods, only the impacts of changes in water quality and quantity could be potentially assessed. For the other impacts, LCIA methods should be further developed to evaluate the impacts on human health and ecosystem quality resulting from these damages. Refer to GESAMP (2019) for a detailed review of the potential damages.

Critical review of the results

The results from attributional LCA of ore-sand presented in this section provide a positive indication on the potential advantages of ore-sand as a substitute for natural sand, as well as of the key factors influencing these results. However, it is still premature to make a definitive conclusion. Aside from a lack of data on ore-sand, the main limitations are:

- A large part of the life cycle assessment is missing as the potential differences in the use and end-of-life phases of the sand-containing products have not been assessed (the analysis is cradle-to-gate instead of cradle-to-grave). The ability to compare the impacts between Vale sand production and river sand extraction in a meaningful way is limited to global warming (GHG emissions). As explained in the description of the LCA of river sand available in Ecoinvent, the disturbances on rivers are not considered adequately. The reduction in impacts resulting from substituting river sand for Vale sand is therefore potentially under-estimated.
- There are currently very few estimates of the extraction impacts of one growing source of sand, namely marine sand. In addition, the data and methods to adequately assess the impacts (except for climate change) of these operations, i.e. the impacts on seabed structure, flora and fauna, are to be further developed. For a recent assessment of industry practices in the UK, refer to Newell and Woodcock (2013).

- The impacts from various tailings management options are currently likely under-estimated. This is because tailings are modelled very simply in LCAs. In the Ecoinvent 3.8 database, estimates are based on generic models of waste landfill adapted to average tailings of metal extraction (Doka, 2018). They are not specific to iron ore production, nor are they site-specific (Muller et al., 2019). In addition, only (wet) dams are modelled, not dry stacking.

Potential GHG reduction of the substitution of natural sand by ore-sand

The annual GHG emissions resulting from the use of aggregates (sand, gravel and crushed rocks) globally, as well as the potential GHG reduction induced by the substitution of natural sand by ore-sand, can be estimated in broad terms by combining the results from this study with global statistics.[26] We estimate this to be in the range of 150 million (a conservative estimate considering only half of the emissions per kg of river sand or crushed rock) to 1 billion tonnes of CO_2-equivalent per year (considering 20 g of CO_2-equivalent per kg of sand, i.e. a value corresponding to the emissions of sand from open-pits and 100 km of delivery by truck). These estimates represent between 0.3% and 2% of global yearly GHG emissions, with the best guess of 1%, i.e. equivalent to half of the emissions induced by the shipping industry globally. These numbers are far from negligible and every action enabling the reduction of GHG emissions should be considered with care. This is even more relevant given that sand use is projected to increase in the future due to expected population and income growth.

9.5 Recommendations for next steps

In order to increase the quality of current estimates and to better evaluate the potential of ore-sand, the following aspects would benefit from further research:

- The creation of a comparative inventory of sand extraction from terrestrial, riverine and marine environment. This would include performing a transparent full LCA in accordance with ISO 14040 standard of a representative iron ore mine in Brazil, including an evaluation of wet tailings versus dry stacking. The results can be then included in a well-used LCA database, e.g. Ecoinvent.
- The development of Life Cycle Impact Assessment (LCIA) methods able to consider adequately the impacts of riverine and marine sand extraction.
- The documentation of applications and testing of products containing ore-sand to complement the tests on ore-sand performed in this project.
- An evaluation per region, as proposed by Friot and Ghallagher (2022), combining (a) an assessment of the current (and future) socio-economic and environmental risks linked to sand, (b) an assessment of the market potential, and (c) an assessment of the availability and potential impacts of the best available alternatives.

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[26] Global sand and aggregates use is estimated to be close to 50 Bt per year (see Section 6). Global GHG emissions are currently close to 50 Bt of CO_2-eq. per year (Richie and Roser, 2020). GHG emissions per kg of crushed rock and gravel are estimated to be between 2 and 4 g of CO_2-eq. without transportation (source: Ecoinvent).

10 The geography of circular economy opportunities

This section describes our approach to mapping and matching worldwide mineral ore extraction and processing with sand and aggregate consumption, aiming to uncover existing and potential hotspots for ore-sand.

10.1 Potential supply of ore-sands

Multiple factors have to be taken into account to estimate the opportunities for alternative sands from mineral ores at the global level. The required data include, but are not limited to:

- the volume of processed mineral ores, recovered commodities, and generated waste;
- waste management practices and existing options for the reuse of mine waste;
- their physicochemical properties;
- required/possible adjustments in the processing circuits and/or reprocessing options to recover (different types of) sand (and aggregates);
- geographic location and climate settings; and
- transportation distances to potential markets.

The initial approach (in this project) takes into account only the first and last of these factors. Essentially, providing a high-level estimate for the mine waste materials that potentially can be transformed into and/or used as alternative sands, though not necessarily equal to the volume of recoverable sand (which is likely to be lower).

To overview all known mining locations and estimate the quantity of processed mineral ores worldwide, we combined information from three sources: The Global Tailings Portal (GTP; Franks et al., 2021), the S&P Global Market Intelligence Database ("S&P"; S&P, 2021), and the United States Geological Survey (USGS) Mineral Commodity Summaries 2021 (USGS, 2021). By developing a method for combining the information from these three databases, we were able to create a global map which has accurate locations of 3852 mine sites, with either direct or indirect estimates of potential ore-sand supply for 2916 sites. These locations are shown in Figure 18.

Where site-specific production or ore processing quantities are not reported in S&P, these are estimated by working backwards from the national and global production totals for 16 major commodities[27] in the USGS dataset. Sites with reported ore-processing estimate were of course still included even if they do not produce any of these 16. For sites that produce multiple commodities, detailed steps are included to avoid the same ore being counted twice.

As well as all the estimates for individual sites, this matching process automatically yields a *lower bound* estimate for the total processed and unused ore globally of 13 Bt. The true value would be expected to greatly exceed this due to the many sites that are presumably absent

[27] Commodities included were: bauxite, cobalt, copper, diamonds, gold, iron, lead, lithium, manganese, molybdenum, nickel, phosphate, platinum, silver, tin, and zinc.

from all 3 of our datasets, or which give insufficient data for ore processing to be estimated by the above method.

10.2 Modelling global consumption

Our starting point to map the global consumption of sand and aggregate was data from the Global Aggregates Information Network (O'Brian et al., 2020) and from the *Union Européenne des Producteurs de Granulats* (UEPG, 2020). Between them, these provide the estimated aggregate production for 54 countries. This dataset was further extended with estimates from three single-country research projects (Lewis et al., 2015, Hinton et al., 2016, Smith et al., 2017). These additional countries greatly increased the breath of economic circumstances that the dataset is sampling, which was important for further modelling below.

These collected estimates for the national *production* of sand and aggregates were then converted to *consumption* estimates by adjusting for the tonnage traded between countries that is reported in the COMTRADE database (DESA/UNSD). Though the coverage of this final dataset of 55 countries is substantial, representing over 35 Bt of aggregate consumption between them, it still leaves more than 100 nations unaccounted for, amounting to over a third of the world's population. The simplest estimate for the consumption in these other countries would be to find average *per-capita* consumption across all the known countries, 7.6 tonnes per person per year, and multiply by the population in the others.

To improve on this, we instead analysed the dataset to reveal how national consumption depends on a countries' other characteristics, such as GDP and Human Development Index (HDI). Strong positive trends were found between both these parameters and per-capita aggregate consumption. These trends were then used to make more grounded estimates of the per capita consumption for the other countries[28].

This exercise revealed that the unlisted countries have, on average, a much lower GDP and lower HDI that those which are members of GAIN or UEPG, as illustrated in Figure 17. The method therefore predicts of a much lower per-capita consumption in these unlisted countries of just 3.1 t/person/year, leading to an estimate for total global aggregate consumption of 45.4 Bt.

Regional data for GDP and HDI (Kummu et al., 2018) allow the variation of the per-capita consumption to not only be predicted at national level, but at regional level. Combined with population data from NASA's Socioeconomic Data and Applications Center (SEDAC), this method generates a map of estimated aggregate consumption with a resolution better than 10 km (5 arcminutes). This distribution is shown in Figure 18.

[28] To avoid false correlations with GDP and HDI, countries where a very high portion of their consumption may be due to land forming (UAE, Qatar, Bahrain, Maldives) were excluded for the prediction process, as were countries where the production/movement of aggregate may not be physically attributable to the country itself (Luxembourg). These data were reinstated after the modelling.

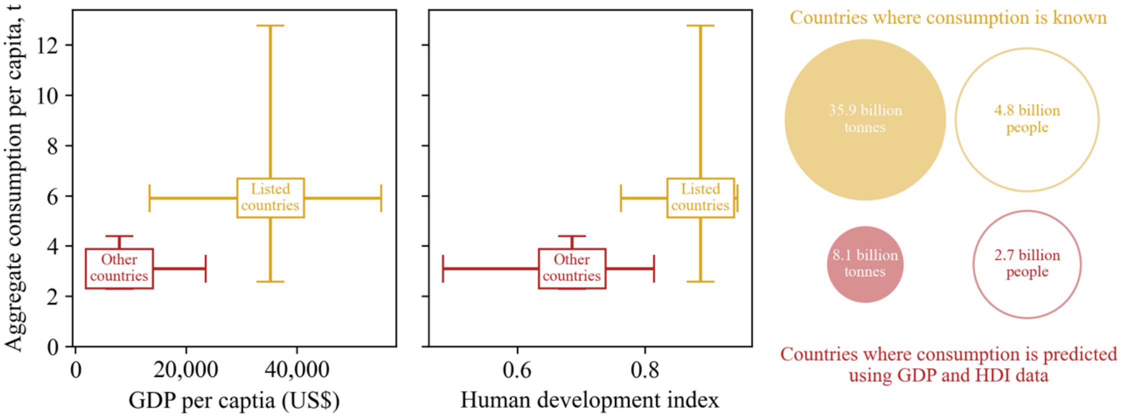

FIGURE 17. PREDICTION OF GLOBAL AGGREGATE CONSUMPTION BY EXTRAPOLATING FROM KNOWN DATA USING CORRELATIONS WITH GDP AND HUMAN DEVELOPMENT INDEX.

Note: Errorbars indicate the 10^{th}-90^{th} percentile of the distribution of each sample and are centred on the median.

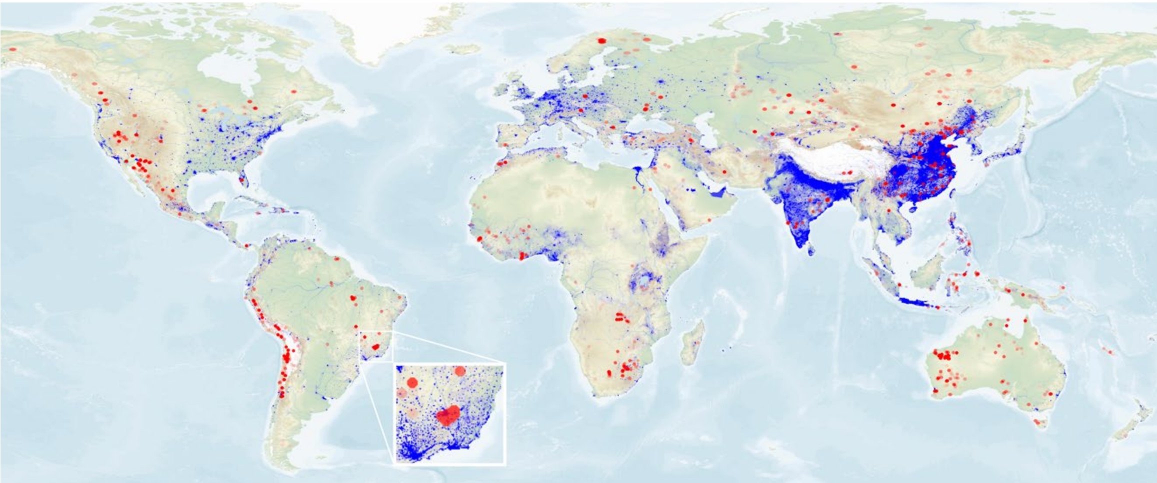

FIGURE 18. A COMPARISON BETWEEN THE DEMAND FOR SAND AND AGGREGATES (BLUE) AND THE POTENTIAL SUPPLY OF ALTERNATIVE AGGREGATES FROM MINERAL ORES (RED).

Note: The potential supply points are shown as points with a radius of 50 km, a typical distance over which transporting sand is economic. The weight of the pixels is proportional to the estimated potential supply at that point, capped at 200 kt. The weight of the blue pixels is proportional to the estimated demand at each location, capped at the same value.

10.3 Comparison of supply locations with demand for sand

Prospects for construction sites looking to use ore-sand

One important question which can be addressed using the data visualised in Figure 18 is how far the sites of sand (and aggregate) consumption typically are from potential sources of ore-sand. To answer this, we found the distance to the closest source for each demand point, and then calculated the distribution of this distance for all sources. The result of this calculation is shown in Figure 19, expressed as a fraction of global demand.

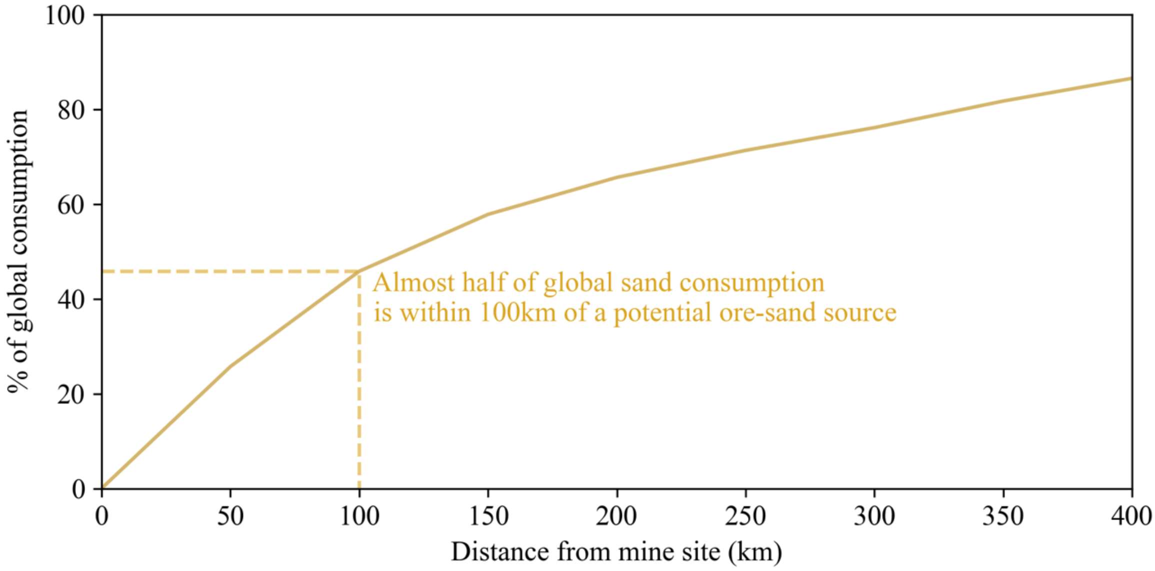

FIGURE 19. A COMPARISON BETWEEN THE LOCATION OF DEMAND FOR AGGREGATE AND SAND, AND THE LOCATION OF MINING PROJECTS.

Figure 19 shows that a very substantial fraction of the world aggregate demand is within range of a potential source of ore-sand. For further analysis, we calculated the distribution of this 'local' demand by country, to reveal in which parts of the world there is the greatest absolute potential for substitution. This is shown in Figure 20. Even on a logarithmic scale, the demand for aggregate in China dominates the figure, representing almost 80% of the total global substitution potential at this distance.

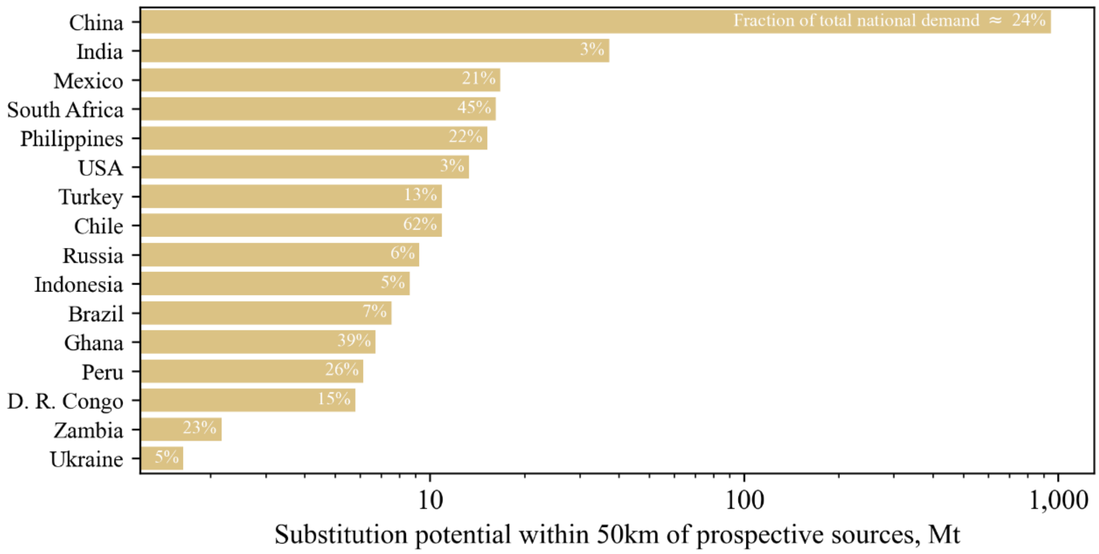

FIGURE 20. ABSOLUTE SUBSTITUTION POTENTIAL WITHIN GROUND TRANSPORT RANGE OF A POTENTIAL ORE-SAND SOURCE.

Whilst the demand in China dominates the global picture in absolute terms, in relative terms there are a great many other countries where the scope for substitution is also very positive. In over 50 countries, the demand fraction that is close to potential sources is over 10%. Figure 21 shows this relative substitution potential for 16 major countries (where the total potential for substitution is over 5 Mt per year).

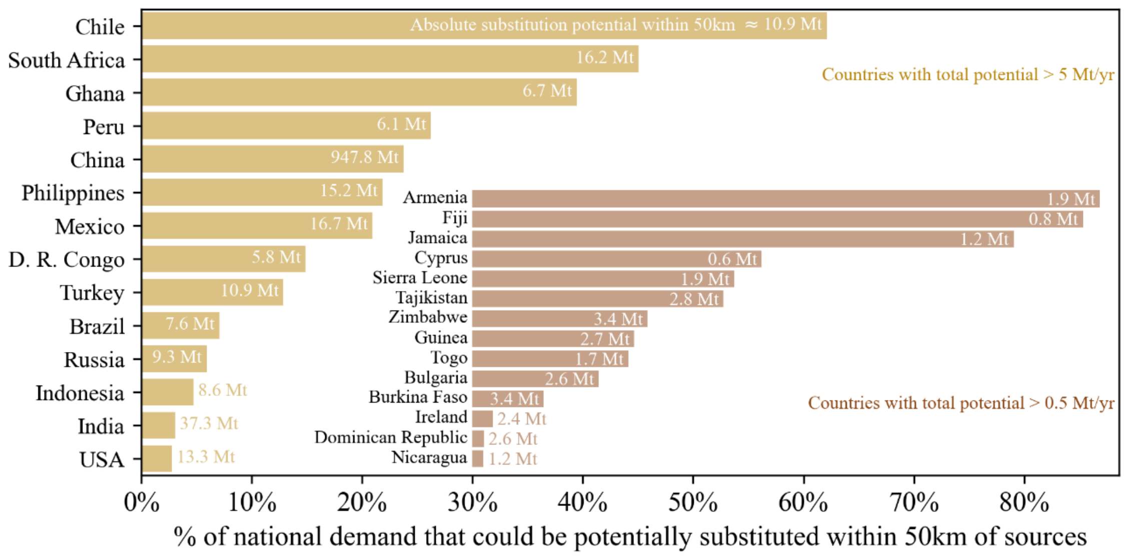

FIGURE 21. RELATIVE SUBSTITUTION POTENTIAL (FRACTION OF TOTAL NATIONAL DEMAND) WITHIN GROUND TRANSPORT RANGE OF A POTENTIAL ORE-SAND SOURCE.

Note: The inset includes a list of countries with a smaller absolute substitution potential (from 0.5 Mt to 5 Mt) but yet significant as a per cent of national demand (with a cut-off at 30%).

Prospects for mine sites looking to find demand

To analyse the data from the perspective of mine sites, we took the 2499 grid points where we have estimates for the potential ore-sand supply and compared this to the demand at increasing distances from each point. The results from all sites were then consolidated into a single histogram, shown in Figure 22.

This analysis reveals that almost a third of all mine sites may find that there is sufficient demand for sand within just 50 km of their site. This is an encouragingly large fraction from the point of view of this project's goals. Furthermore, the hatched distribution in Figure 22 compares potential ore-sand supply with the total aggregate demand (not just sand fraction). In an idealised future scenario, greater pre-sorting may enable coarser aggregate production in addition to ore-sand. In this case, almost half of all mining projects could find sufficient local demand for these combined co-products.

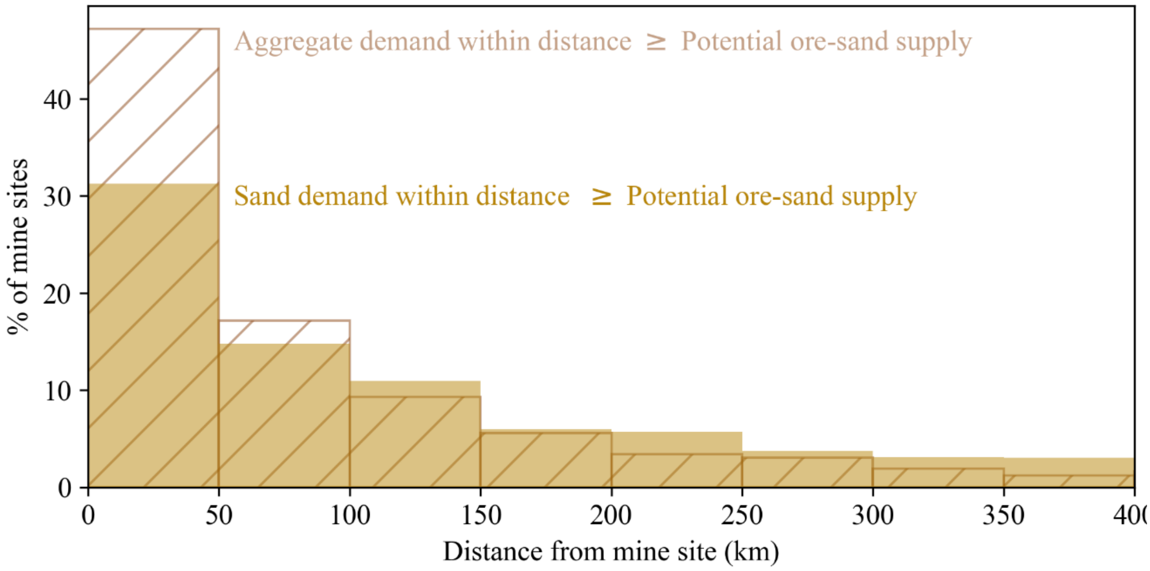

FIGURE 22. COMPARISON OF POTENTIAL ORE-SAND SUPPLY WITH THE ESTIMATED DEMAND FOR SAND IN THE SURROUNDING AREAS.

11 Conclusions and recommendations

This section summarises the results from the project and provides recommendations for ore-sand production and use. In addition, it also indicates the role of different stakeholders in addressing and building a bridge over the chasm for ore-sands to become a potential solution to the mine tailings and sand sustainability crises, aligning mining and mineral processing with the circular economy.

A call for action to address the sand sustainability crisis

The awareness that sand is a strategic resource is growing. It is a vital resource for economic development, and naturally-occurring sand is a key component for climate resilience and ecosystems.

Demand for sand will increase with population growth, migration from rural to urban environments and growing need for infrastructure tied to development, as well as for climate change adaptation. Yet, all indications are that we are approaching a future where access to this resource is a critical barrier to sustainability, and the full costs of uncontrolled sand extraction come due. Extraction rates of sand from dynamic natural systems are exceeding natural sand replenishment rates in many parts of the world (UNEP, 2019). Awareness of sand sustainability is therefore generating clear calls for alternatives to naturally occurring sand at scale.

Ore-sand as a solution to mine tailings sustainability crisis

Safe storage and disposal of mine waste associated with the extraction and supply of resources to the global economy is one of the major environmental challenges, recently exacerbated by the catastrophic failures of large mine tailings storage facilities. Attempts to reuse mining residues have been made in the past but without any significant uptake, with the major reasons being the enormous amount of these materials and difficulty to meet the quality specifications in different applications. Although, the only market that is comparable with the volume of mine waste at the global scale is construction aggregates, including sand.

In contrast with previous attempts to reuse different mine waste in construction applications, ore-sand is a product by design. With some changes and adjustments in the mineral processing operations, the required properties of sand as a marketable product and comparable with naturally-sourced sands can be achieved. Moreover, the opportunities for ore-sand recovery should be best taken into account at the design stage, e.g. in the development of new mineral deposits. Co-production of ore-sand (and the recovery of other by-products) may also help to offset some technical, economic, and environmental challenges with lower grade ores and deposits, currently foreseen as one of the major challenges in future mining, otherwise generating even more mine waste if compared to mines currently in operation.

Given that certain ore bodies are associated with minerals and potentially harmful and hard to remove trace elements, a thorough evaluation of the mineral ores and their transformation through mineral processing is required to ensure production of ore-sand which is safe to use. Future research should therefore focus on the evaluation of the suitability of different types of ore bodies and mineral processing pathways for ore-sand production and their classification.

Offsetting sand derived from dynamic ecosystems

The substitution of marine or river sand by ore-sand does not only depend on the technical feasibility but also on the overall economics, regulation, building traditions and the need for environmentally sustainable alternatives. This means that the conditions for the adoption of ore-sand may be determined locally despite its technical feasibility. The resource substitution strategies look most opportune and realistic when:

- local availability of naturally-sourced sand or recycled materials does not meet the needs;
- there are constraints on mine waste generation and storage that incentivize innovation;
- transportation costs for naturally-sourced sands are relatively high compared to sourcing sand from elsewhere, including alternative aggregate materials;
- there are clear incentives and interest in trying alternative sands from an environmental and regulatory point of view.

The potential is even more pronounced when we consider that the tailings storage facilities that present the highest safety risks to people (those located near where people live) offer the greatest opportunity of finding a market for ore-sand (because of the local demand for the material).

Cross-sectoral dialogue and collaboration

Engaging in cross-sectoral dialogue with industries and standard-setting institutes with an interest in sand and gravel procurement or use offers multiple opportunities for introducing alternative sands into the aggregate markets. This will help identify new market partners, including standard-setting institutes which can facilitate setting-up new opportunities to research, test and promote ore-sand’s adoption.

As confirmed by stakeholder interviews with aggregate market players, to cross the innovation chasm it is essential to promote pilot projects for real world results, showcasing the material’s easy-win and replicability, with an emphasis on the material’s performance, durability, and sourcing process. These lesson-learning, stakeholder engagement and networking opportunities will help provide real-world testimonies. One avenue into construction markets is by finding allies within the sustainable infrastructure landscape, where ore-sand can be a sustainably and responsibly procured alternative, in line with end-users’ organisational goals, values and past experiences.

Current technical limitations and opportunities

Based on the results from the case-study in this project, it can be concluded that ore-sands, such as Vale sand, already offer promising opportunities for partial substitution of river and marine sand in many applications. Although, it is important to highlight the fine nature of current ore-sands, which is a product of the fine grinding of many mineral processing circuits. Consequently, at present ore-sand can mainly replace another fine sand but not coarse sand required in different applications. Yet, there are opportunities for generating coarser materials while at the same time maintaining the recovery of the primary ore by adjusting current operations and/or introducing new technologies (such as through coarse grinding, coarse particle flotation and/or pre-sorting).

From a technical perspective, ore-sand from iron ore mining operations can, for example, provide a direct replacement for naturally-sourced sand in the following applications:

- fine aggregates used as a part of road subbase;
- fine aggregates in bricks manufacturing;
- infill sand for land reclamation if the percentage of fines is limited (e.g. below 15%);
- silica and iron oxide raw material additives for cement clinker manufacturing.

Blending with coarser sand and aggregates – whether naturally-sourced, manufactured or recycled – would be required (but may not be sufficient) for:

- (conventional) concreting and mortar applications;
- construction fill (although fine sand can be accepted in some cases);
- agricultural use – for soil improvement and drainage;
- water treatment.

There are also opportunities for better and/or additional reprocessing of sand derived from mineral ores which could help obtain sand with high silica content, meeting the requirements, for example, for glass manufacturing. In this case, this would be an example of complete replacement of naturally-sourced sand.

Sustainability considerations and market niche

Introducing alternative sands into aggregate markets requires developing and honing a well-crafted market niche. This entails having sustainability standards which can transparently and reliably guarantee best practice in sand extraction, production and recycling. Such standards already prove their value in infrastructure projects but currently do not properly address sand sourcing and material efficiency. Having such sustainability standards would help with telling an authentic story, and provide the opportunity to develop and showcase ore-sand's compatibility to these standards. Indeed, aggregate market players increasingly perceive strong calls to engage in sustainability certification processes across the sand value chain, including for extraction, transport, industrial and construction sector applications. It reflects that the aggregates and industrial sand sourcing landscape is changing, with carbon reduction becoming increasingly part of construction companies' tendering applications and often embedded within contracts' sustainability criteria.

Simultaneously, the life cycle assessment of ore-sand, based on the case of Vale sand, shows that substituting naturally-sourced sand by ore-sand could potentially lead to net reductions in carbon emissions induced during sand production. In many cases, the carbon emissions along the sand supply chain are, however, dominated by emissions from transportation. The proximity and type of transport of ore-sand production sites to places of demand will thus probably play a critical role in its acceptability with respect to climate change mitigation. The substitution of marine or riverine sand by ore-sand could also lead to a reduction in ecosystem damage. However, an adequate comparison of the potential impacts of the various forms of sand production and extraction is currently not possible. Such assessment requires the development of a new comparative inventory of sand production as well as the development of Life Cycle Impact Assessment (LCIA) methods able to consider adequately these impacts.

Safeguarding sustainable and just transitions

There is a range of factors that could jeopardise or prevent wider adoption of ore-sands in the markets and the achievement of sustainable and just transitions. These range from the presence of contaminants, and changes in the management of (residual) tailings and other environmental impacts at the mine site, to broader effects on the market, including displacement of traditional practices in sand extraction such as by artisanal and small-scale miners. Most of those factors have to be assessed on the case-by-case basis, and in many areas further research is still needed. Yet, publicly sharing the knowledge and examples of best practices in the recovery, supply, and use of ore-sands in different applications could allow to avoid unintentional negative impacts. A close collaboration between mining industry, construction sector, and other stakeholders is important to uncover the limitations and capitalize on the opportunities with ore-sands.

Future markets for ore-sands

The analysis of mining locations worldwide revealed that almost a third of mine sites can find at least some demand for ore-sand within a 50 km range, which could contribute to at least 10% reduction in the volume of tailings generation at each site. With inclusion of opportunities for coarser construction materials production, almost half of mine sites could find local demand for aggregate by-products. Looking at the potential ore-sand supply from a consumer (or construction industry) point of view, at least half of the global sand market (by volume) may find a local source of ore-sand.

However, there is a still a significant number of mining operations that would probably not find sufficient off-site demand for ore-sand even within 500 km, either because they are remote or generate large quantities of tailings, or both. Where mine sites are far from construction markets they may not be in a position to easily source construction materials for their own needs and ore-sands may therefore be useful for onsite use. The uptake of ore-sand market opportunities offsite for sites far from markets will require effective transport systems (e.g. rail networks linked to ports), and primarily target global markets for sand and aggregate materials.

The current list of potential major producers of ore-sand with local proximity to markets is dominated by China, but also includes India, Mexico, Indonesia, South Africa, the Philippines, Turkey, USA, and Chile. With an increase in urban population requiring significant new infrastructure development, promising hotspots for the uptake of ore-sand opportunities will likely include different parts of Africa, in particular Southern Africa and West Africa. Nevertheless, at the local level, there seems to be many places around the world where the potential demand and supply of ore-sand could meet, contributing to simultaneously addressing the global sand sustainability and mine waste management challenges.

References

Aerts, J.C., Barnard, P.L., Botzen, W., Grifman, P., Hart, J.F., De Moel, H., Mann, A.N., de Ruig, L.T. & Sadrpour, N. (2018). Pathways to resilience: adapting to sea level rise in Los Angeles. *Annals of the New York Academy of Sciences, 1427* (1), 1-90. https://doi.org/10.1111/nyas.13917

Allacker, K., Mathieux, F., Pennington, D., Pant, R. (2017). The search for an appropriate end-of-life formula for the purpose of the European Commission Environmental Footprint initiative. *The International Journal of Life Cycle Assessment* 22(9), 1441-1458. https://doi.org/10.1007/s11367-016-1244-0

Aneke, F. I., & Shabangu, C. (2021). Green-Efficient Masonry Bricks Produced from Scrap Plastic waste and Foundry Sand. *Case Studies in Construction Materials*, e00515. https://doi.org/10.1016/j.cscm.2021.e00515

ASTM C144-18, (2018). Standard Specification for Aggregate for Masonry Mortar. ASTM International, West Conshohocken, PA.Bamberger, M., Tarsilla, M., & Hesse-Biber, S. (2016). Why so many "rigorous" evaluations fail to identify unintended consequences of development programs: How mixed methods can contribute. *Evaluation and Program Planning*, *55*, 155–162. https://doi.org/10.1016/j.evalprogplan.2016.01.001

ASTM D2487-00, (2000). Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System). ASTM International, West Conshohocken, PA, 12 p.

ASTM International. (n.d.). About us. https://www.astm.org/about/overview.html

Aumônier, S., Hartlin, B. & Peirce, A. (2010). Carbon footprint of marine aggregate extraction. *Environmental Resources Management Limited (ERM).* https://www.thecrownestate.co.uk/media/2481/ei-carbon-footprint-of-marine-aggregate-extraction.pdf

Bahn-Walkowiak, B., Bleischwitz, R., Distelkamp, M., & Meyer, M. (2012). Taxing construction minerals: a contribution to a resource-efficient Europe. *Mineral Economics 25* (1), 29-43 https://doi.org/10.1007/s13563-012-0018-9

Bendixen, M., Best, J., Hackney, C., & Iversen, L. L. (2019). Time is running out for sand. *Nature*, *571*(7763), 29–31. https://doi.org/10.1038/d41586-019-02042-4

Bendixen, M., Iversen, L.L., Best, J., Franks, D.M., Hackney, C.R., Latrubesse, E.M., Tusting, L.S. (2021). Sand, gravel, and UN Sustainable Development Goals: Conflicts, synergies, and pathways forward. *One Earth* 4(8), 1095-1111.

Bendixen, M., Overeem, I., Rosing, M. T., Bjørk, A. A., Kjær, K. H., Kroon, A., Zeitz, G., & Iversen, L. L. (2019). Promises and perils of sand exploitation in Greenland. *Nature Sustainability*, *2*(2), 98–104. https://doi.org/10.1038/s41893-018-0218-6

Benson, T. (2019). Digital innovation evaluation: User perceptions of innovation readiness, digital confidence, innovation adoption, user experience and behaviour change. *BMJ Health & Care Informatics*, *26*, 6. https://doi.org/10.1136/ bmjhci-2019-000018

Bhardwaj, B., & Kumar, P. (2017). Waste foundry sand in concrete: A review. *Construction and Building Materials*, *156*, 661–674. https://doi.org/10.1016/j.conbuildmat.2017.09.010

Bisht, A. (2021). Conceptualizing sand extractivism: Deconstructing an emerging resource frontier. *The Extractive Industries and Society*, *8*(2), 100904. https://doi.org/10.1016/j.exis.2021.100904

Boos, S., & Dahlstrom, A. (2015). *Coastal Evolution at Nha Trang Bay, Vietnam. Water Resources Engineering.* [Master's thesis, Lund University]. TVVR-15/5006. http://lup.lub.lu.se/luur/download?func=downloadFile&recordOId=7448002&fileOId=7448014

Boussaa, S. A., Kheloufi, A., Zaourar, N. B., & Bouachma, S. (2017). Iron and aluminium removal from Algerian silica sand by acid leaching. *Acta Physica Polonica A*, 132(3), 1082-1086.

Broothaers, L. (2000). Zandboek Vlaanderen. Ministerie van de Vlaamse Gemeenschap, afdeling Natuurlijke Rijkdommen en Energie. https://publicaties.vlaanderen.be/view-file/251

Brown, J. (Ed.). (2000). Foseco Ferrous Foundryman's Handbook. Butterworth-Heinemann.

BS 1199 and 1200:1976. (1999). British Standard. Building sands from natural sources. British Standards Institute, London.

BS 6349 – 5. (1991). British Standard. Maritime structures, part 5. Code of practice for dredging and land reclamation. British Standards Institute, London.

BSI. (2022). What is the national standards body? https://www.bsigroup.com/en-GB/about-bsi/uk-national-standards-body/what-is-the-national-standards-body

Bureau of Indian Standards. (2018). International Standardization Activity. 2 November 2018. https://www.bis.gov.in/index.php/standards/standard-formulation/international-standardization-activity/

Campos, A., López, C.M., Blanco, A., Aguado, A. (2018). Effects of an internal sulfate attack and an alkali-aggregate reaction in a concrete dam. *Construction and Building Materials* 166, 668-683.

Cashore, B. (2002). Legitimacy and the Privatization of Environmental Governance: How Non-State Market-Driven (NSMD) Governance Systems Gain Rule-Making Authority. *Governance*, *15*(4), 503–529. https://doi.org/10.1111/1468-0491.00199

CEN. (2019). The 'New Approach'. 14 June 2019. https://boss.cen.eu/reference-material/guidancedoc/pages/newapproach/

Charmaz, K., & Belgrave, L. L. (2015). Grounded Theory. In G. Ritzer (Ed.), *The Blackwell Encyclopedia of Sociology* (p. wbeosg070.pub2). John Wiley & Sons, Ltd. https://doi.org/10.1002/9781405165518.wbeosg070.pub2

Che, T. K., Pan, B. F., Sha, D., & Lu, J. L. (2019). Utilization of iron tailings as fine aggregates in low-grade cement concrete pavement. *IOP Conference Series: Materials Science and Engineering*, 479(1). https://doi.org/10.1088/1757-899X/479/1/012053

Chinnappa, G. B., & Karra, R. C. (2020). Experimental and Statistical Evaluations of Strength Properties of Concrete with Iron Ore Tailings as Fine Aggregate. *Journal of Hazardous, Toxic, and Radioactive Waste*, *24*(1), 04019038. https://doi.org/10.1061/(ASCE)HZ.2153-5515.0000480

Choplin, A. (2020). Matière grise de l'Urbain: la vie du ciment en Afrique. Genève: MétisPresses, 2020. https://archive-ouverte.unige.ch/unige:145150

Ciganek, A. P., Haseman, W. (Dave), & Ramamurthy, K. (2014). Time to decision: The drivers of innovation adoption decisions. *Enterprise Information Systems*, *8*(2), 279–308. https://doi.org/10.1080/17517575.2012.690453

Coelho, J.M. (2001). The Mining of Aggregates in the Metropolitan Region of São Paulo. IIED and WBCSD, no 121.

Comaroff, J. (2014). Built on sand: Singapore and the new state of risk. (No. 39; pp. 138–147). *Harvard Design Magazine*. http://www.harvarddesignmagazine.org/issues/39/built-on-sand-singapore-and-the-new-state-of-risk

COPOLCO. (n.d.). Consumers and Standards: Partnership for a Better World. ISO. https://www.iso.org/sites/ConsumersStandards/1_standards.html

Corbin, J. M., & Strauss, A. L. (2015). Basics of qualitative research: Techniques and procedures for developing grounded theory (Fourth edition). SAGE.

Cui, L., Wang, L., Xu, Y., Lou, X. and Wang, H. (2021). Feasibility Evaluation of Replacing River Sand with Copper Tailings. *Sustainability*, *13*(14), p.7575.

Dean, R. G., & Dalrymple, R. A. (2004). Coastal processes with engineering applications. Cambridge University Press.

Dearden, J., Ickes, B. W., & Samuelson, L. (1990). To Innovate or Not to Innovate: Incentives and Innovation in Hierarchies. *The American Economic Review*, *80*(5), 1105–1124.

Delgado, J., Guimarães, A., De Freitas, V., Antepara, I., Kočí, V., Černý, R. (2016). Salt damage and rising damp treatment in building structures. *Advances in Materials Science and Engineering,* 2016.

Di Pierro, S. (2021). Raw Materials for Glassmaking: Properties and Constraints. *Encyclopedia of Glass Science, Technology, History, and Culture*, 1, 39-51.

Dittrich, M., & Bringezu, S. (2010). The physical dimension of international trade. *Ecological Economics*, *69*(9), 1838–1847. https://doi.org/10.1016/j.ecolecon.2010.04.023

Doh, J. P., & Pearce, J. A. (2004). Corporate Entrepreneurship and Real Options in Transitional Policy Environments: Theory Development. *Journal of Management Studies*, *41*(4), 645–664. https://doi.org/10.1111/j.1467-6486.2004.00448.x

Doka G. (2018). A model for waste-specific and climate-specific life cycle inventories of tailings impoundments – Version 2. Doka Life Cycle Assessments, Zurich, Switzerland. Available at: http://www.doka.ch/publications.htm

Dong, Q., Liang, B., Jia, L., Jiang, L. (2019). Effect of sulfide on the long-term strength of lead-zinc tailings cemented paste backfill. *Construction and Building Materials* 200, 436-446.

Ecoinvent Association (2021). System Models. https://ecoinvent.org/the-ecoinvent-database/system-models/

EN ISO 14688-1:2018. (2018). Geotechnical investigation and testing – Identification and classification of soil – Part 1: Identification and description. Comité Européen de Normalisation, Brussels.

European Commission DG Grow. (n.d.) Standardisation Policy. https://ec.europa.eu/growth/single-market/european-standards/standardisation-policy_en

European Commission DG Trade. (2019). Commission Implementing Regulation (EU) 2019/1198 of 12 July 2019 imposing a definitive anti-dumping duty on imports of ceramic tableware and kitchenware originating in the People's Republic of China following an expiry review pursuant to Article 11(2) of Regulation (EU) No 2016/1036. C/2019/5208. Official Journal of the European Union. 12 July 2019. https://eur-lex.europa.eu/eli/reg_impl/2019/1198/oj

European Commission. (2010). *General guide for Life Cycle Assessment: Provisions and action steps*. Joint Research Centre. Institute for Environment and Sustainability. Publications Office. https://data.europa.eu/doi/10.2788/94987

Evans, A.M. (1993). Ore Geology and Industrial Minerals: An Introduction. Oxford, London.

Fang, H.Y., Yang, J.H., Chen, Q. (2018). Particle size distribution and energy consumption during impact crushing of single granite particles. *J. S. Afr. Inst. Min. Metall. vol.118 n.5*. http://dx.doi.org/10.17159/2411-9717/2018/v118n5a12

Ferreira, H. & Garcia Praça Leite G. (2015). A Life Cycle Assessment study of iron ore mining, *Journal of Cleaner Production, 108*(A), 1081-1091. https://doi.org/10.1016/j.jclepro.2015.05.140

Filho, J. N. S., Da Silva, S. N., Silva, G. C., Mendes, J. C., & Peixoto, R. A. F. (2017). Technical and Environmental Feasibility of Interlocking Concrete Pavers with Iron Ore Tailings from Tailings Dams. *Journal of Materials in Civil Engineering*, 29(9), 04017104. https://doi.org/10.1061/(asce)mt.1943-5533.0001937

Finnveden, G., Hauschild, M. Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D. & Suh, S. (2009). Recent developments in Life Cycle Assessment. *Journal of Environmental Management*, *91* (1), 1-21. https://doi.org/10.1016/j.jenvman.2009.06.018

Fontes, W. C., Mendes, J. C., Da Silva, S. N., & Peixoto, R. A. F. (2016). Mortars for laying and coating produced with iron ore tailings from tailing dams. *Construction and Building Materials*, 112, 988–995. https://doi.org/10.1016/j.conbuildmat.2016.03.027

Franks, D. M. (2020). Reclaiming the neglected minerals of development. *The Extractive Industries and Society*, 7(2), 453–460. https://doi.org/10.1016/j.exis.2020.02.002

Franks, D. M., Boger, D. V., Côte, C. M. & Mulligan, D. R. (2011), Sustainable development principles for the disposal of mining and mineral processing wastes. *Resources Policy* 36(2), 114–122 (2011).

Franks, D. M., Stringer, M., Torres-Cruz, L. A., Baker, E., Valenta, R., Thygesen, K., Matthews, A., Howchin, J., & Barrie, S. (2021). Tailings facility disclosures reveal stability risks. *Scientific Reports*, *11*(1), 5353. https://doi.org/10.1038/s41598-021-84897-0

Franks, D.M., Ngonze, C., Pakoun, L. and Hailu, D. (2020). Voices of artisanal and small-scale mining, visions of the future: report from the International Conference on Artisanal and Small-scale Mining and Quarrying. *Extractive Industries and Society*, 7(2):505-511. https://doi.org/10.1016/j.exis.2020.01.011

Franks, D.M., Pakoun, L. and Ngonze, C. (2016). Development Minerals: Transforming a neglected sector in Africa, the Caribbean and the Pacific. United Nations Development Programme.

Friese, S. (2016). CAQDAS and Grounded Theory Analysis. *MMG Working Paper,* (16-07).

Friot, D. & Gallagher, L. (2021). An early exploration of data and knowledge availability for sand resources status. Part 1. Identification of sand data and knowledge gaps: Setting priorities for further research. Technical report GSOI-GSA-2021-001.P1. *UNEP/GRID-Geneva,* Geneva. DOI:10.13140/RG.2.2.29853.23527.

Friot, D. & Gallagher, L. (2022) An early exploration of data availability for the creation of an inventory on sand extraction and tracking resources status. Part 2: Best available quantitative assessments of sand production, trade and consumption. Technical report GSOI-GSA-2021-001.P2. *UNEP/GRID-Geneva*, Geneva.

Gaasbeek, A. & Meijer, E. (2013). Handbook on a Novel Methodology for the Sustainability Impact Assessment of New Technologies. Report prepared within the EC 7th Framework.

Gambhir M. L. (2013). Concrete Technology, 5th edition. McGraw Hill Education (India) Private Ltd, New Delhi.

Gaulier, G. & Zignago, S. (2010). BACI: International Trade Database at the Product-Level (the 1994-2007 Version) (October 2010). CEPII Working Paper 2010-23. http://dx.doi.org/10.2139/ssrn.1994500

GESAMP. (2019). SCOPING ACTIVITIES CG 5: Sand and Gravel Mining in the Marine Environment – New Insights on a Growing Environmental Problem. 46th session, agenda item 4. http://www.gesamp.org/site/assets/files/2058/46_7_4.pdf

Ghassim, B., & Bogers, M. (2019). Linking stakeholder engagement to profitability through sustainability-oriented innovation: A quantitative study of the minerals industry. *Journal of Cleaner Production*, *224*, 905–919. https://doi.org/10.1016/j.jclepro.2019.03.226

Golev, A., Lebre, E., Corder, G. (2016). The contribution of mining to the emerging circular economy. *AusIMM Bulletin*, December 2016, 30-32. https://www.ausimmbulletin.com/feature/the-contribution-of-mining-to-the-emerging-circular-economy

Golev, A., Manlapig, E., Corder, G., Jones, J., Mandaran, K., Edraki, M., Hourn, M., Radulovic, P. (2017). Conceptual integrated strategy for mine tailings reprocessing and land rehabilitation, *Enviromine Srmining* 2017. 8-10 November. Santiago, Chile.

GWP. (2010). A study of silica sand quality and end uses in Surrey and Kent. Final report. GWP Consultants LLP. https://gwp.uk.com/wp-content/uploads/2016/04/Silica-Sand-March-2010-Report-Final.pdf

Harben, P.W. (2002). The Industrial Minerals Handybook: A Guide to Markets, Specifications & Prices (fourth ed.). Industrial Minerals Information Ltd., London.

Hargrave, T. J., & Van De Ven, A. H. (2006). A Collective Action Model of Institutional Innovation. *Academy of Management Review*, *31*(4), 864–888. https://doi.org/10.5465/amr.2006.22527458

Henry, M. S., Bazilian, M. D., & Markuson, C. (2020). Just transitions: Histories and futures in a post-COVID world. *Energy Research & Social Science*, *68*, 101668. https://doi.org/10.1016/j.erss.2020.101668

Huang, X., Ranade, R., Ni, W., & Li, V. C. (2013). Development of green engineered cementitious composites using iron ore tailings as aggregates. *Construction and Building Materials*, 44, 757–764. https://doi.org/10.1016/j.conbuildmat.2013.03.088

ICMM (2019). Integrated mine closure: Good practice guide, 2nd edition. International Council on Mining and Metals. https://www.icmm.com/en-gb/guidance/environmental-stewardship/integrated-mine-closure-2019

ICMM, UNEP, & PRI. (2020). *Global Industry Standard on Tailings Management* (Global Mine Tailings Review, p. 39). United Nations Environment Programme (UNEP), Principles for Responsible Investment (PRI) and International Council on Mining and Metals (ICMM). https://globaltailingsreview.org/wp-content/uploads/2020/08/global-industry-standard-on-tailings-management.pdf

Innis, S., & Kunz, N. C. (2020). The role of institutional mining investors in driving responsible tailings management. *The Extractive Industries and Society*, *7*(4), 1377–1384. https://doi.org/10.1016/j.exis.2020.10.014

IRP. (2020). Mineral Resource Governance in the 21st Century: Gearing extractive industries towards sustainable development. Ayuk, E. T., Pedro, A. M., Ekins, P., Gatune, J., Milligan, B., Oberle B., Christmann, P., Ali, S., Kumar, S. V, Bringezu, S., Acquatella, J., Bernaudat, L., Bodouroglou, C., Brooks, S., Buergi Bonanomi, E., Clement, J., Collins, N., Davis, K., Davy, A., Dawkins, K., Dom, A., Eslamishoar, F., Franks, D., Hamor, T., Jensen, D., Lahiri-Dutt, K., Mancini, L., Nuss, P., Petersen, I., Sanders, A. R. D. International Resource Panel. United Nations Environment Programme. https://www.resourcepanel.org/reports/mineral-resource-governance-21st-century

IS 2116. (1980). Sand for masonry mortars – Specification. Bureau Of Indian Standards, New Dehli.

Ismail, Z. Z., & AL-Hashmi, E. A. (2008). Reuse of waste iron as a partial replacement of sand in concrete. *Waste Management*, 28(11), 2048–2053. https://doi.org/10.1016/j.wasman.2007.07.009

ISO 14040:2006. (2006). Environmental management — Life cycle assessment — Principles and framework. International Organization for Standardization. Retrieved from: https://www.iso.org/standard/37456.html.

ISO. (n.d. a). *ABOUT US MEMBERS*. https://www.iso.org/members.html

ISO. (n.d. b). *ABOUT US*. https://www.iso.org/about-us.html

Jolliet, O., Margni, M., Charles, R., Humbert, S., Payet, J., Rebitzer, G., Rosenbaum R. (2003). IMPACT 2002+: A new life cycle impact assessment methodology. *The International Journal of Life Cycle Assessment*, 8 (324). https://doi.org/10.1007/BF02978505

Jonkman, SN., Hillen, MM., Nicholls, RJ., Kanning, W., & van Ledden, M. (2013). Costs of adapting coastal defences to sea-level rise new estimates and their implications. *Journal of Coastal Research: an international forum for the Littoral Sciences, 29*(5), 1212-1226. https://doi.org/10.2112/JCOASTRES-D-12-00230.1

Kapoor, K. K., Dwivedi, Y. K., & Williams, M. D. (2014). Rogers' Innovation Adoption Attributes: A Systematic Review and Synthesis of Existing Research. *Information Systems Management*, *31*(1), 74–91. https://doi.org/10.1080/10580530.2014.854103

Kaza, S., Yao, L., Bhada-Tata, P., Van Woerden, F. (2018). What a waste 2.0: a global snapshot of solid waste management to 2050. World Bank Publications. https://datatopics.worldbank.org/what-a-waste/trends_in_solid_waste_management.html

Kempkens, M. (2015). *The Development of Innovation A broader view facing the continuous and relentless quest for progress, improvement and innovation.* [A thesis submitted to the Department of Architecture in conformity with the requirements for the degree of Masters's of science, University of Technology, Delft]. https://tinyurl.com/yvn634ar

Keppert, M., Scheinherrová, L., Jerman, M., Doušová, B., Kobera, L., Brus, J., Černý, R. (2018). Hydration of Ordinary Portland Cement in Presence of Lead Sorbed on Ceramic Sorbent. *Materials* 12(1), 19.

Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling*, *127*, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005

Kumar, B. N. S., R, S., Shet, S. U., & Srishaila, J. M. (2014). Utilization Of Iron Ore Tailings As Replacement To Fine Aggregates In Cement Concrete Pavements. *International Journal of Research in Engineering and Technology*, 03(07), 369–376. https://doi.org/10.15623/ijret.2014.0307063

Kundu, S., Aggarwal, A., Mazumdar, S., & Dutt, K. B. (2016). Stabilization characteristics of copper mine tailings through its utilization as a partial substitute for cement in concrete: preliminary investigations. *Environmental Earth Sciences*, 75(3), 1–9. https://doi.org/10.1007/s12665-015-5089-9

Kuranchie, F. A., Shukla, S. K., Habibi, D., & Mohyeddin, A. (2015). Utilisation of iron ore tailings as aggregates in concrete. *Cogent Engineering*, 2(1), 1083137. https://doi.org/10.1080/23311916.2015.1083137

Landfield, A.H., Karra, V. (2000). Life cycle assessment of a rock crusher. *Resources, Conservation and Recycling 28,* 207–217.

Leal Filho, W., Hunt, J., Lingos, A., Platje, J., Vieira, L. W., Will, M., & Gavriletea, M. D. (2021). The Unsustainable Use of Sand: Reporting on a Global Problem. *Sustainability*, *13*(6), 3356. https://doi.org/10.3390/su13063356

Liekefett, K. H. E., Gregory, H., J., & Wood, S. A. L. (2021, May 29). *Shareholder Activism and ESG: What Comes Next, and How to Prepare*. Harvard Law School Forum on Corporate Governance. https://corpgov.law.harvard.edu/2021/05/29/shareholder-activism-and-esg-what-comes-next-and-how-to-prepare/

Linham, M.M., Green, C.H., and Nicholls, R.J. (2010). *Costs of adaptation to the effects of climate in the world's largest port cities.* Report 14 of the AVOID programme (AV/WS2/D1/R14). 225 pp.

Lottermoser, B.G. (2010). Mine Wastes (third edition): Characterization, treatment and environmental impacts. Springer, Berlin.

Lottermoser, B.G. (2011). Recycling, reuse and rehabilitation of mine wastes. *Elements*, 7, 405-410.

Lund, S., Manyika, J., Woetzel, J., Barriball, E., Krishnan, M., Alicke, K., Birshan, M., George, K., Smit, S., Swan, D. and Hutzler, K. (2020). Risk, resilience, and rebalancing in global value chains. McKinsey Global Institute. https://www.mckinsey.com/business-functions/operations/our-insights/risk-resilience-and-rebalancing-in-global-value-chains

Matejka, L., Siler, P., Novotny, R., Svec, J., Masilko, J., Soukal, F. (2021). Negative effect of zinc compounds on hydration kinetics of ordinary Portland cement, IOP Conference Series: Materials Science and Engineering. IOP Publishing, p. 012004.

Mazzucato, M. (2011). The entrepreneurial state. *Soundings*, *49*(49), 131–142. https://doi.org/10.3898/136266211798411183

Menton, M., Milanez, F., Souza, J. M. de A., & Cruz, F. S. M. (2021). The COVID-19 pandemic intensified resource conflicts and indigenous resistance in Brazil. *World Development*, *138*, 105222. https://doi.org/10.1016/j.worlddev.2020.105222

Molina-Castillo, F.-J., Lopez-Nicolas, C., & Soto-Acosta, P. (2012). Interaction effects of media and message on perceived complexity, risk and trust of innovative products. *European Management Journal*, *30*(6), 577–587. https://doi.org/10.1016/j.emj.2012.07.005

Moore, G. A. (2014). *Crossing the chasm: Marketing and selling disruptive products to mainstream customers* (Third edition). HarperBusiness, an imprint of HarperCollins Publishers.

MPA. (n.d.). *CPR & CE Marking*. https://mineralproducts.org/Mineral-Products/CPR-CE-Marking.aspx

Mudd, G.M., Boger, D.V. (2013). The ever growing case for paste and thickened tailings: Towards more sustainable mine waste management. *AusIMM Bulletin*, 56-59.

Muller, S., Lassin, A., Lai, F., Guignot, S. (2019). Taking into account final mining wastes in LCA: How to quantify the impacts of tailings? LCM 2019, Sep 2019, Poznan, Poland. hal-02154855.

Newell, R.C., & Woodcock, T.A. (2013). Aggregate Dredging and the Marine Environment: an overview of recent research and current industry practice. *The Crown Estate*, 165pp. ISBN: 978-1-906410-41-4.

Norgate T., Haque, N. (2010). Energy and greenhouse gas impacts of mining and mineral processing operations. *Journal of Cleaner Production 18*, 266–274.

Northey, S. A., Mudd, G. M., & Werner, T. T. (2018). Unresolved Complexity in Assessments of Mineral Resource Depletion and Availability. *Natural Resources Research*, *27*(2), 241–255. https://doi.org/10.1007/s11053-017-9352-5

O'Brien, J. (2019). Aggregates in growth mode. *International Cement Review*. June 2019, 46-51. https://www.cemnet.com/

OECD & ISO. (2016). *International Regulatory Co-operation and International Organisations: The Case of the International Organization for Standardization (ISO)*. OECD and ISO. https://www.oecd.org/gov/regulatory-policy/ISO_Full-Report.pdf

Okeyinka, O. M., Oloke, D. A., & Khatib, J. M. (2015). A Review on Recycled Use of Solid Wastes in Building Materials. *International Journal of Civil, Environmental, Structural, Construction and Architectural Engineering*, 9(12), 1502–1511. https://doi.org/10.5281/zenodo.1110481

Onuaguluchi, O., & Eren, Ö. (2013). Rheology, strength and durability properties of mortars containing copper tailings as a cement replacement material. *European Journal of Environmental and Civil Engineering*, 17(1), 19–31. https://doi.org/10.1080/19648189.2012.699708

Otten, G.R., Visser, M.A.J. & Wijmenga, P.S.J. (2002). *Sectoranalyse van de sector bouwgrondstoffenvoorziening in Nederland*. Netherlands Economic Institute (ECORYS-NEI, Rotterdam). Report AC7181 PW/SJS 29-11-02. 53 pp.

Padmalal, D. & Maya, K. (2014). *Sand Mining. Environmental Impacts and Selected Case Studies*. Springer, India. DOI 10.1007/978-94-017-9144-1.

Pavez, O., González, L., Vega, H., & Rojas, E. (2016). Copper tailings in stucco mortars. *REM - International Engineering Journal*, 69(3), 333–339. https://doi.org/10.1590/0370-44672015690148

Pavez, O., Rivera, O., Toledo, I., & Nazer, A. (2018). Use of copper slag as fine aggregate and partial replacement of cement. *HOLOS*, 4(7), 31–45. https://doi.org/10.15628/holos.2018.6736

Peduzzi, P. (2014). Sand, rarer than one thinks. *Environmental Development*, 11, 208-218.

Polhill, J. G., Ge, J., Hare, M. P., Matthews, K. B., Gimona, A., Salt, D., & Yeluripati, J. (2019). Crossing the chasm: A 'tube-map' for agent-based social simulation of policy scenarios in spatially-distributed systems. *GeoInformatica*, *23*(2), 169–199. https://doi.org/10.1007/s10707-018-00340-z

Protasio, F. N. M., Avillez, R. R. de, Letichevsky, S., & Silva, F. de A. (2021). The use of iron ore tailings obtained from the Germano dam in the production of a sustainable concrete. *Journal of Cleaner Production*, 278(123929), 17. https://doi.org/10.1016/j.jclepro.2020.123929

Pszonka, J., Sala, D., 2018. Application of the mineral liberation analysis (MLA) for extraction of grain size and shape measurements in siliciclastic sedimentary rocks, E3S Web of Conferences, Volume 66. AG 2018 – 4th International Conference on Applied Geophysics. Cracow, Poland, June 28-29, 2018.

Rabobank. (2013). *Dredging - Profit margins expected to remain fairly healthy until 2018*. https://dredging.org/media/ceda/org/documents/resources/othersonline/rabobank-outlook_dredging_september_2013.pdf

Raffaelli, R. and Glynn, M.A. (2015). Institutional Innovation: Novel, Useful. In: The Oxford Handbook of creativity, innovation, and entrepreneurship, pp.407-420.

Rathor, A., Pradhan, M., Deo, S. (2020). Assessment of Coal Mine Overburden Sand for Use in Concrete Making as Fine Aggregate. *International Journal of Advanced Research in Engineering and Technology*, 11.

Reddy, B.R., Satyanarayanan, K.S. and Jagannatha, H. (2016). Use of gold mine tailings in production of concrete- A feasibility study. *International Journal of Earth Sciences and Engineering, 9(3), 197–202.*

Reed, M. S., Graves, A., Dandy, N., Posthumus, H., Hubacek, K., Morris, J., Prell, C., Quinn, C. H., & Stringer, L. C. (2009). Who's in and why? A typology of stakeholder analysis methods for natural resource management. *Journal of Environmental Management*, *90*(5), 1933–1949. https://doi.org/10.1016/j.jenvman.2009.01.001

Reuter, M.A., Heiskanen, K., Boin, U., van Schaik, A., Verhoef, E., Yang, Y., Georgalli, G. (2005). The metrics of material and metal ecology. Elsevier, Amsterdam.

Ritchie, H. & Roser, M. (2020). CO_2 and Greenhouse Gas Emissions. Published online at OurWorldInData.org. Retrieved from: https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions.

Roche, C., Thygesen, K. & Baker, E. (eds.). (2017). Mine Tailings Storage: Safety Is No Accident. A UNEP Rapid Response Assessment: United Nations Environment Programme and GRID-Arendal, Nairobi and Arendal, www.grida.no.

Rogers, E. M. (2010). *Diffusion of Innovations* (4th Edition). Simon and Schuster.

Rogers, K. H., Luton, R., Biggs, H., Biggs, R. (Oonsie), Blignaut, S., Choles, A. G., Palmer, C. G., & Tangwe, P. (2013). Fostering Complexity Thinking in Action Research for Change in Social– Ecological Systems. *Ecology and Society*, *18*(2), art31. https://doi.org/10.5751/ES-05330-180231

Rosstandard. (2020). *Euroasian interstate council (EASC)*. 2 March 2020. https://www.rst.gov.ru/portal/eng//home/cooperation/eacs

S&P Global. (2021). S&P Global Market Intelligence. Thomson Reuters. https://www.snl.com/.

Sala, E., Mayorga, J., Bradley, D. et al. (2021). Protecting the global ocean for biodiversity, food and climate. Nature 592, 397–402. https://doi.org/10.1038/s41586-021-03371-z

Saldaña, J. (2013). The coding manual for qualitative researchers (2nd ed). SAGE.

Salmimies, R., Mannila, M., Kallas, J., Häkkinen, A. (2011). Acidic dissolution of magnetite: experimental study on the effects of acid concentration and temperature. *Clays and clay minerals*, 59, 136-146.

Scalet B, Garcia Munoz M, Sissa A, Roudier S, Delgado Sancho L. (2012). Best Available Techniques (BAT) Reference Document for the Manufacture of Glass. Industrial Emissions Directive 2010/75/EU (Integrated Pollution Prevention and Control). EUR 25786 EN. Luxembourg: Publications Office of the European Union. https://publications.jrc.ec.europa.eu/repository/handle/JRC78091

Schlindwein, S.L. and Ison, R. (2004). Human knowing and perceived complexity: implications for systems practice. *Emergence: Complexity and Organization*, 6(3), 27-32.

Seal, R. R., & Piatak, N. M. (2017). Environmental Attributes and Resource Potential of Mill Tailings from Diverse Mineral Deposit Types. *IMWA 2017*, Lappeenranta, Finland.

SEDAC. (2021). Gridded Population of the World (GPW), v4. Socioeconomic Data and Applications Center. https://sedac.ciesin.columbia.edu/data/collection/gpw-v4/documentation

Shalley, C. E., Hitt, M. A., & Zhou, J. (Eds.). (2016). The Oxford handbook of creativity, innovation, and entrepreneurship (First issued as an Oxford University Press paperback). Oxford University Press.

Shen, W., Yang, Z., Cao, L., Cao, L., Liu, Y., Yang, H., Lu, Z., Bai, J. (2016). Characterization of manufactured sand: Particle shape, surface texture and behavior in concrete. Construction and Building Materials 114, 595-601.

Shettima, A. U., Hussin, M. W., Ahmad, Y., & Mirza, J. (2016). Evaluation of iron ore tailings as replacement for fine aggregate in concrete. *Construction and Building Materials*, 120, 72–79. https://doi.org/10.1016/j.conbuildmat.2016.05.095

Shi, C., Meyer, C., & Behnood, A. (2008). Utilization of copper slag in cement and concrete. *Resources, Conservation and Recycling*, 52(10), 1115–1120. https://doi.org/10.1016/j.resconrec.2008.06.008

Shi, X., Mukhopadhyay, A., & Zollinger, D. (2018). Sustainability assessment for portland cement concrete pavement containing reclaimed asphalt pavement aggregates. *Journal of Cleaner Production*, *192*, 569–581. https://doi.org/10.1016/j.jclepro.2018.05.004

Sibelco. (2019). Sibelco and responsible sand production. Available online: https://www.sibelco.com/wp-content/uploads/ResponsibleIndustrialSandProduction_web.pdf.

Speybroeck, J., Bonte, D., Courtens, W., Gheskiere, T., Grootaert, P., Maelfait, J. P., Degraer, S. (2006). Beach nourishment: an ecologically sound coastal defence alternative? A review. *Aquatic conservation: Marine and Freshwater ecosystems*, 16(4), 419-435.

Strambach, S., & Pflitsch, G. (2020). Transition topology: Capturing institutional dynamics in regional development paths to sustainability. *Research Policy*, *49*(7), 104006. https://doi.org/10.1016/j.respol.2020.104006

Stryja, C., & Satzger, G. (2018). Try Before You Buy: How to Design Information Systems to Enhance Consumer Willingness to Test Sustainable Innovations. *Journal of Technology Management & Innovation*, *13*(1), 19–26. https://doi.org/10.4067/S0718-27242018000100019

SuRe® Standard (ST01 ENG Version 2.0). (2021). Global Infrastructure Basel Foundation. http://www.gib-foundation.org

Sverdrup, H. U., Koca, D., & Schlyter, P. (2017). A Simple System Dynamics Model for the Global Production Rate of Sand, Gravel, Crushed Rock and Stone, Market Prices and Long-Term Supply Embedded into the WORLD6 Model. *BioPhysical Economics and Resource Quality*, *2*(2), 8. https://doi.org/10.1007/s41247-017-0023-2

Swetha, Kumar, S., Bhavya, & Anadinni. (2015). Characterization Of Materials By Partially Replacing Cement By Copper Ore Tailing And Sand By Iron Ore Tailing. *International Journal of Research in Engineering and Technology*, 04(07), 374–377. https://doi.org/10.15623/ijret.2015.0407060

Swilling, M. (2020). *The age of sustainability: Just transitions in a complex world*.

Taxiarchou, M., Panias, D., Douni, I., Paspaliaris, I., Kontopoulos, A. (1998). Dissolution of magnetite in acidic oxalate solutions. *Transactions of the Institution of Mining and Metallurgy: Section C*, 107, C37.

Tian, Z., Zhao, Z., Dai, C., & Liu, S. (2016). Experimental Study on the Properties of Concrete Mixed with Iron Ore Tailings. *Advances in Materials Science and Engineering*, 2016, 1–9. https://doi.org/10.1155/2016/8606505

Tixier, R., Devaguptapu, R., Mobasher, B. (1997). The effect of copper slag on the hydration and mechanical properties of cementitious mixtures. *Cement and Concrete Research* 27, 1569-1580.

Torres, A., Brandt, J., Lear, K., & Liu, J. (2017). A looming tragedy of the sand commons. *Science*, *357*(6355), 970–971. https://doi.org/10.1126/science.aao0503

Torres, A., Simoni, M. U., Keiding, J. K., Müller, D. B., zu Ermgassen, S. O. S. E., Liu, J., Jaeger, J. A. G., Winter, M., & Lambin, E. F. (2021). Sustainability of the global sand system in the Anthropocene. *One Earth*, *4*(5), 639–650. https://doi.org/10.1016/j.oneear.2021.04.011

Turnheim, B., Berkhout, F., Geels, F., Hof, A., McMeekin, A., Nykvist, B., & van Vuuren, D. (2015). Evaluating sustainability transitions pathways: Bridging analytical approaches to address governance challenges. *Global Environmental Change*, *35*, 239–253. https://doi.org/10.1016/j.gloenvcha.2015.08.010

Ugama, T. I., & Ejeh, S. P. (2014). Iron Ore Tailing As Fine Aggregate In Mortar Used For Masonry. *International Journal of Advances in Engineering & Technology*, 7(4), 1170–1178. https://doi.org/10.1.1.669.8652

Ugama, T. I., Ejeh, S. P., & Amartey, D. Y. (2014). Effect of Iron Ore Tailing on the Properties of Concrete. *Civil and Environmental Research*, 6(10), 8. www.iiste.org

Ulsen, C., Antoniassi, J.L., Martins, I.M., & Kahn, H. (2021). High quality recycled sand from mixed CDW – is that possible? *Journal of Materials Research and Technology, 12*, 29-42. https://doi.org/10.1016/j.jmrt.2021.02.057.

UNEP (2019). Sand and sustainability: Finding new solutions for environmental governance of global sand resources : synthesis for policy makers. United Nations Environment Programme, Nairobi.

UNEP (2021). *International Good Practice Principles for Sustainable Infrastructure.* United Nations Environment Programme, Nairobi.

UNEP/GRID-Geneva. (2021). What is Sand - Results from a UNEP/GRID-Geneva expert discussion.

USGS (2019). *2016 Minerals Yearbook, Silica* [Advance Release]. U.S. Geological Survey. March 2016. https://prd-wret.s3-us-west-2.amazonaws.com/assets/palladium/production/atoms/files/myb1-2016-silic.pdf

USGS (2021). *Mineral Commodity Summaries 2021.* U.S. Geological Survey. https://doi.org/10.3133/mcs2021.

Vale (2020). Integrated report 2020. http://www.vale.com/brasil/pt/business/reports/siteassets/relato-integrado-2020/assets/docs/vale_integrated_report_2020.pdf

Vatalis, K.I., Charalambides, G., & Benetis, N.P. (2015). Market of high purity quartz innovative applications. *Procedia Economics and Finance, 24,* 734-742. https://doi.org/10.1016/S2212-5671(15)00688-7

Wang, Y.-S., Wu, S.-C., Lin, H.-H., Wang, Y.-M., & He, T.-R. (2012). Determinants of user adoption of web ''Automatic Teller Machines': An integrated model of 'Transaction Cost Theory' and 'Innovation Diffusion Theory'. *The Service Industries Journal*, *32*(9), 1505–1525. https://doi.org/10.1080/02642069.2010.531271

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B. (2016). The ecoinvent database version 3 (part I): overview and methodology. *The International Journal of Life Cycle Assessment* 21(9), 1218-1230. https://doi.org/10.1007/s11367-016-1087-8

Wright, H., Dimsdale, T., Healy, C., Williamson, S., & Mabey, N. (2018). *Sustainable infrastructure and the multilateral development banks: Changing the Narrative* (p. 22) [Briefing Note]. E3G. https://www.jstor.org/stable/pdf/resrep21743.pdf

Xu, Q. (2020). Situation and Suggestion of Geology and Mineral Resources Standardization. In C. Huang, Y.-W. Chan, & N. Yen (Eds.), *Data Processing Techniques and Applications for Cyber-Physical Systems (DPTA 2019)* (pp. 893–898). Springer Singapore.

Yellishetty, M., Karpe, V., Reddy, E. H., Subhash, K. N., & Ranjith, P. G. (2008). Reuse of iron ore mineral wastes in civil engineering constructions: A case study. *Resources, Conservation and Recycling,* 52(11), 1283–1289. https://doi.org/10.1016/j.resconrec.2008.07.007

Zhang, W., Gu, X., Qiu, J., Liu, J., Zhao, Y., & Li, X. (2020). Effects of iron ore tailings on the compressive strength and permeability of ultra-high performance concrete. *Construction and Building Materials*, 260, 119917. https://doi.org/10.1016/j.conbuildmat.2020.119917

Zhao, J., Ni, K., Su, Y., & Shi, Y. (2021). An evaluation of iron ore tailings characteristics and iron ore tailings concrete properties. *Construction and Building Materials*, 286, 122968. https://doi.org/10.1016/j.conbuildmat.2021.122968

Zhao, S., Fan, J., & Sun, W. (2014). Utilization of iron ore tailings as fine aggregate in ultra-high performance concrete. *Construction and Building Materials*, 50, 540–548. https://doi.org/10.1016/j.conbuildmat.2013.10.019

Technical Annexes

A. Project outreach & engagement

Title	Platform	Date
Conferences and forums		
The Environmental Impacts of Offshore Mining	ASEAN-IGF Mining and Sustainability Forum	Jul 27, 2021
Alternative sand from mineral ores	SMI Tailings Masterclass	Sept 6, 2021
Equity, Ecosystems and Scarcity - The Global Sand Crisis and Infrastructure	IUCN World Conservation Congress	Sept 8, 2021
The Elephant in the Extractives Rooms: The neglected value of sand	World Resources Forum	Oct 12, 2021
A discussion towards principles on policy for the just & responsible governance & management of sand	UNEP/GRID-GVA Sand Roundtable	Oct 12, 2021
Waste Management and Valorisation for a Sustainable Future	Nature Conferences	Oct 26-28, 2021
Work Integrated Learning and Action Research Program	UNESCO-IGCP: Stone for Development	Nov 25, 2021
Media Outlets		
Mineral ores may help prevent sand sustainability crisis	Mining.com	Dec 13, 2021
Mineral ores to sand out sustainability crisis	Australian Mining	Dec 14, 2021

B. Stakeholder interview research design

B.1 Interviewee selection

- Stakeholders previously in contact with GRID-Geneva on the topic of sand and sustainability.
- LinkedIn search procedures.
- Literature searches.
- Recommendations from other interviewees.
- Country case selections based on gaps in available literature and needed complements to the strong knowledge on European and Asian aggregates markets already held by the project team.

B.2 Interview protocol

A basic protocol was designed to frame semi-structured interviews being undertaken to generate data for two complementary but separate research procedures: the current research project discussed in this document and a second targeting an understanding of the policy conditions and practices for extraction of sand from the natural environment. The protocol was adapted for different stakeholders with question numbering kept consistent across interview sheets to assist with recording of data in database form when interview numbers grow to the point where a quantitative data analysis is worthwhile. Interviews were conducted in English or French, as preferred by the interviewee.

B.3 Data management procedure

Stakeholders were given a unique identity code to anonymise data. Interviews were recorded with the consent of interviewees and the video data stored in a secure location, only accessible to the University of Geneva project team.

B.4 Qualitative data coding and analysis procedure

Following a grounded theory approach (Charmaz and Belgrave, 2015), in-vivo coding approach was used to the first reading of our data (Saldaña, 2016). The lead researcher recorded ideas and thoughts throughout the analysis process that related to:

1. Key steps, impacts and effects of sourcing of sand from the natural environment, including extractive processes, transport modalities, materials flows to key demand sectors.
2. Promising alternative materials and the barriers and incentives supporting their adoption, including specific regulatory instruments for post-consumption materials management, construction sector performance standards and regulations, supply concerns, economic conditions, sustainability concerns, personal attitudes and perceptions of other stakeholder attitudes and other factors contributing to or impeding uptake of alternative sands.
3. Descriptions of key characteristics or elements required for responsible sourcing of sand, including alternatives to sand.

We used computer-assisted qualitative analysis [ATLAS.ti software package] (Friese 2016) for the second phase of data analysis after 20 interviews were completed.

C. Independent Scientific Committee members & process

Purpose and Objectives of the Scientific Committee

Members of the Scientific Committee are expected to assess and provide professional opinion on the project activities and outcomes, such as:

1. Review sampling and analysis methods and protocols and provide timely advice.
2. Provide advice on interpretation of results.
3. Inform the project team of opportunities to coordinate activities with other initiatives (past and present) and assist to form partnerships with collaborators relevant to the project.
4. Bring to the attention of the project team cutting edge scientific and policy findings of relevance to achieve the project objectives.
5. Distribute final knowledge products through professional networks.
6. Attend quarterly online meetings of the committee.

Membership and Function

1. Members of the Scientific Committee will be invited by the project team.
2. Members are expected to hold positions within government, international agencies, academic, policy or technical institutions, or inter-industry associations.
3. Membership will reflect diverse geographic, gender and institutional representation.
4. Membership is voluntary and will not be remunerated.
5. Membership is for the duration of the project (1-year).
6. Members are expected to act with discretion and maintain the confidentiality of non-public documents and information.
7. Members shall hold a Bachelors Degree in a relevant discipline with either a) a Masters Degree or higher or b) 10 years of professional experience in a relevant field.
8. Members are expected to be fluent in English, writing and speaking.
9. The Committee will have a maximum of 5 (five) members.
10. The project team will act as the secretariat of the Committee and provide administrative support for Committee meetings.
11. The Committee is not responsible for management of the project and will not make, or issue, decisions or statements on its own behalf.
12. Inactive members of the Committee may be asked to resign their membership.

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