Resource Management and a Best Available Concept for Aggregate Sustainability

S. W. Danielsen[1]*, E. Kuznetsova[1,2]

[1] SINTEF Building and Infrastructure, Høgskoleringen 7A, NO-7465, Trondheim, Norway,
[2] NTNU Norwegian University of Science and Technology, NO-7465, Trondheim, Norway
*SveinWilly.Danielsen@sintef.no, Elena.Kuznetsova@ntnu.no

Tables: 2, Figures: 3, number of words: 6009, number of references: 33

Aggregates are major constituents in construction, the global request for which approaches some 22 billion tonnes per year. Some major challenges follow; first of all the dependency on geological conditions and the availability of resources; secondly the traffic, emissions and energy use connected with transportation; thirdly the technology of utilising resources with a variety of properties to meet user requirements; and finally – getting more awareness – the land use conflicts and environmental impact of the aggregate and quarrying industry, and the need for making these activities sustainable.

Aggregate standards have primarily been written by engineers. And engineers are first of all concerned with technical requirements. However, in the future, there will be a greater focus on environmental impact and sustainability.

Geological resources are non-renewable, which e.g. can be seen in the rapid depletion of natural sand/gravel deposits. This causes increasing awareness along with environmental impact; conflicts of interest concerning land-use; sustainability in mass balance; and not least – increasing transport distances required to get the materials to the places of use.

The principle of a Best Available Concept (BAC) for aggregate production and use is introduced, working with four essential phases: Inventory and planning, Quarrying and production, Use of aggregates, and Reclamation of mined-out areas. In order to compare alternatives and calculate environmental and economic consequences of decisions, it is recommended to work with new LCC (Life Cycle Cost) and LCA (Life Cycle Assessment) tools recently developed in two EU (European Union) funded research projects.

Keywords: Aggregates, BAC, Construction, LCC/LCA, Sustainability

The access to materials has been identified as one of the major global drivers in the years to come. This will also apply to natural aggregates – sand, gravel, and crushed stone –, which are essential resources for use in construction and by far the most used material worldwide, second only to water (Langer *et al.* 2004). Despite the fact that natural aggregate is widely distributed throughout the world, it is not necessarily available for use. For example, some areas do not have sand or gravel, or in other areas, natural aggregate does not meet the quality requirements for use or may react adversely (Langer *et al.* 2004; Langer 2009).

Aggregates make up some 70 % of the volume of concrete and 90 % of road pavements, and are indispensable constituents for the construction industry (Brown *et al.* 2013, Neeb 2013). During 1998, worldwide, about 20 billion tonnes of aggregate worth about 120 billion Euros were produced (Wellmer & Becker-Platen 2002). Worldwide demand is estimated to be rising by 4.7% annually (Bleischwitz & Bahn-Walkowiak 2006). But today most countries are facing a fast coming shortage of traditional aggregate resources, firstly sand and gravel (Langer *et al.* 2004).

The consumption of sand/gravel as construction aggregates accelerated a generation ago, at the beginning of the post-war era of major construction and infrastructure projects. In Norway the construction of large off-shore structures, bridges, dams and office buildings in concrete resulted in a rapid depletion of the glaciofluvial sand/gravel deposits. Aggregates from these sources were also to a large degree exported for use in European infrastructure projects. As a result of this it has been estimated by the present authors that as much as 80 % of all Norwegian, glaciofluvial sand/gravel ever extracted from the nature may have been taken out during the last generation. According to estimations made by Langer and co-authors (2004) during the period between the year 2000 and year 2025 United States will use almost as much construction aggregate as it was used in the entire 20th century. Depletion of resources, new materials alternatives, environmental impacts, land use and neighbour conflicts, transport pollution, all call for a holistic concept for production and use, and tools for choosing and prioritising, which incorporate a lot more factors and issues than simply the mechanical criteria normally ruling alone in the materials standards.

Future standards and specifications should be based on a broad sustainability valuation, taking into account – along with the traditional technical criteria – economic considerations as well as environmental impact and resource management.

The main goal of this paper is to show the local, geology based character for the aggregates and propose Best Available Concepts (BAC), which are holistic and use the latest developments in LCC (Life Cycle Cost) and LCA (Life Cycle Assessment) techniques to come up with environmentally friendly priorities.

Aggregates and Sustainability

Mineral resources can only be extracted where nature has placed them. This has during the years led to materials technology and materials standards being developed nationally based on the properties of the raw materials available, which again has been closely linked to the national or regional geological setting. On the other hand, the mineral resources have to be used where society needs them, which is not necessarily close to the place of extraction. This in turn has led to an ever increasing need for transport to serve the market with aggregates (EUAA 2011).

Aggregate production is, by the strictest definition, non-sustainable, since aggregate resources are non-renewable. But to maintain our current lifestyle, we must have access to a readily available supply of suitable resources. The question here is not the choice between aggregate development and the environment, but how to achieve a balance among the economic, social, and environmental aspects of aggregate resource development (Langer *et al.* 2004; Šolar *et al.* 2004, 2012). However, the term sustainability can be used to characterize an aggregate production which is in an optimum balance with the geological resources used, as well as with the various kinds of physical and societal surroundings (Danielsen & Ørbog 2000). Any exploitation of natural resources should give a maximum of added value to the society, without causing a need for re-deposition or pollution, or being in conflict with the Construction Products Directive (CPD) (EC 1989).

Quarrying and transport of materials have environmental impacts on the local neighbourhood and society, for instance with regard to noise, dust, pollution, and effects on biodiversity (Langer *et al.* 2004). Furthermore, there are land-use conflicts between quarrying and agriculture, recreation, building sites and archaeology, especially in densely populated regions. The aggregate production has often been characterised by inferior mass balance (e.g. high percentages of surplus material) (Smith *et al.* 2002). The biggest challenge facing the aggregate industry will probably be to introduce resource management strategies to meet the environmental requirements while, at the same time, maintaining profitable day-to-day production.

The sustainability issues that are most pressing in relation to the aggregate industry are:

1) Mineral resources,
2) Land use,
3) Mass balance and surplus materials,
4) Energy use, and
5) Pollution and emissions (e.g. from transport).

A holistic view will be vital, not focusing on one or few parameters.

Mineral Resources

With natural sand/gravel resources being rapidly depleted (Bleischwitz **&** Bahn-Walkowiak 2006), the needs of the construction industry will have to be met increasingly from alternatives, like crushed/manufactured and recycled aggregates (Cepuritis 2014). For instance in Norway, with a traditional abundance of glaciofluvial sand gravel, the last decades have seen a marked transition from sand/gravel to crushed rock in the market: while in the 1980ies 50-60 % of the production value in the aggregate sector could be ascribed to natural sand/gravel the corresponding figure today is 20 % and decreasing (Brown *et al.* 2013). On the other hand Norway has a very low percentage of recycled aggregates, being due to a combination of scattered population/few big cities, abundance of suitable rock, and a low degree of demolition. Opposite of this is the situation in the Netherlands, where sand is being increasingly substituted by recycled aggregates, and there is hardly any solid rock to be crushed for construction purpose.

Several countries are currently applying resource taxation and/or regulations, to limit the exploitation of scarce sand/gravel resources. And even approvals for new hard rock quarries are getting more and more difficult to obtain in most European countries, especially close to the markets where the aggregates are needed.

Land Use

Land use conflicts are more and more often the reason for turning down new quarry applications, or even to prolong existing ones (Bloodworth *et al.* 2009). This can be the case in populated areas where competition versus other prioritised purposes, and also neighbourhood protests, are intense, as well as in the countryside where preservation of an un-touched nature is a main issue. If we reconsider the competing land-uses, all types of mining and quarrying in the EU-15 during 2003 were estimated to use 0.2% of the land compared with 0.6% for industry, commerce, energy production, and wastewater treatment; 2.0% for transportation infrastructure; 2.3% for residential; and 41.5% for agriculture (EUROSTAT 2003). The impact is even less when considering aggregate mining alone. For Germany, the land used for the extraction of sand, gravel, and crushed rock was equivalent to less than 0.005% of the total area of Germany (Langer 2009).

Nevertheless, aggregate extraction and processing cause environmental impacts including changes to the landscape, noise, dust, vibrations from blasting, and degradation of groundwater and surface water (Langer 2009). Most people rely on the commodity of the infrastructure for everyday life; however, very few want to live next to a quarry. This causes conflicts regarding e.g. land-use, noise and dust (Willis & Garrod 1999). But the demand for new buildings and improved infrastructure is increasing. Part of the problem is that public authorities in many countries do not have an over-all resource strategy, where the long term need for and supply of crucial materials is balanced against other land use and preservation issues. Incorporated in such a strategy should also be possibilities to use a quarry after it has been closed, making the value of the area increase, e.g. for waste depositing, housing, industry, recreation areas and lakes.

Mass balance and surplus materials

One of the main challenges in aggregate production, especially when producing crushed aggregates from hard rock quarries (Wigum *et al.* 2004, Cepuritis 2014), is to obtain a satisfactory mass balance (Langer *et al.* 2004, Smith *et al.* 2002). Any excess fraction that has to be kept on stock, or deposited, creates an economic as well as an environmental problem. To meet a good mass balance is not only a question of production, but also the society's demand for products and their properties. A consequence of good mass balance is the extended lifetime of the resource. The Norwegian experience is that if quarries are well planned and the production is end-use oriented, surplus material is rarely a problem. Ultimately, no-waste production should be a goal within the aggregate industry. However, the responsibility is not only the producers'. Authorities need to formulate their view on how these issues are to be handled, and materials standards as well as materials research should take up a priority for using the whole range of aggregate sizes produced, not only limited to key size fractions. The development in resource availability strongly challenges the concept of mass balance. With a tendency in the market towards more fine crushed materials and a use of key size fractions, the percentage of e.g. minus 4 mm crushed sand from a hard rock quarry may be of the order of 30 %. At the same time, a technology of utilising such materials in e.g. concrete is not fully developed and implemented throughout Europe. A consequence is huge amounts of surplus, fine-grained materials. If e.g. 1.5 billion tonnes of the total European aggregate production are crushed hard rock materials, approximately 500 million tonnes will be in the size range < 4 mm – and probably at least half of this will have to be deposited, due to lack of application technology and market.

Energy consumption

The energy issue is a very complicated one, owing to an assortment of energy types used and various geological settings (Hammond & Jones 2008). It involves the aggregate production as well as the transport and the final application of the aggregates. The energy consumption per ton of produced aggregates is relatively small compared to the energy consumption of other construction materials (Danielsen *et al.* 2004). Some approximate key figures (in MJ/kg):

- Sea dredged sand: 0,03
- Crushed granite: 0,07
- Cement (depending on type): 7 – 10
- Steel: 40

Aggregate plants are either fixed or mobile; fixed plants normally use electricity whereas mobile units run on fossil fuel. With regard to efficiency, comparison of these two types of plants is difficult. The type of energy used also depends much on the geological setting: producing aggregates from crushed rock requires more energy for processing than excavating sand and gravel. The latter, however, use more energy for transportation within the quarry itself, partly due to the extensive use of wheel loaders.

Considering these numbers, it shall be taken into account that one cannot compare the energy consumption for 1 kg of steel, cement and aggregates respectively. Focus must be on the functional unit in which the materials are used (e.g. 1 m^3 of concrete). The numbers only give an idea of energy consumption related to the first two phases of the life cycle; extraction and production).

Taking into account that the production of 1 m^3 of concrete typically requires about 2 tonnes of aggregates and 300 kg of cement, the energy consumption associated with cement production is still 20 times higher than that associated with aggregate production.

Pollution and emission, e.g. from transport

In many situations the great energy and cost impact is linked to the materials transport – from the quarry to the customer. Aggregate is loaded on trucks, railcars, barges, or freighters for transport to a destination. Aggregate is a high-bulk, low value commodity, and transportation can add substantially to the cost at the point of use (Langer 2009). For example, the cost of transportation of aggregates in the European Union is about 13% of the total cost of the aggregate (Bleischwitz & Bahn-Walkowiak 2006).

Probably the issue of emissions resulting from transport, not least CO_2, will be even more important from an environmental point of view. In a European perspective the figures published in the Mineral Statistics (Brown *et al.* 2013) are interesting: Total cross border export in Europe is of the order of 120 mill. tonnes, while total imports are about 117 mill. tonnes. The two major exporters are Germany and Norway, where Norway (without any import) is the biggest net exporter with approx. 21 mill. tonnes in 2011, even though their share of total European production is only 2,8 %. This also means that Norway exports 29 % of a total aggregate production of 77 mill. tonnes. A graphical presentation of Norwegian aggregate export according to the Norwegian Geological Survey, NGU (Dahl & Eriksen 2013) is presented in Figure 1.

But also in-land transport of aggregates is continuously increasing, for the same reasons as said already. According to NGU (Dahl & Eriksen 2013), average transport distance by car for crushed and natural aggregates was 18 and 22 km respectively, and ship transport distances were similarly 199 and 121 km. Based on figures used in an on-going research project (Wigum *et al.* 2009), it can be estimated that Norwegian in-land transport of aggregates contribute with a CO_2 emission of approx. 140.000 tonnes pr. year. Extrapolating these figures to include European long-range export and also the longer distances that will be typical within many countries between quarries and place of use, it will be realistic to estimate an average equivalent road transport of some 40 km, which for 2.5 billion tonnes means 100 billion ton-km per year, which will be responsible for something of the order of 10-15 mill. tonnes of CO_2 emission.

A Best Available Concept (BAC) for aggregate production and use

The combination of a geology dependency and a great variety of user conditions has made it unrealistic to come up with one single set of Best Available Technologies (BAT's) for aggregate production and use (Danielsen *et al.* 2006). Rather there should be a continuous development of a BAC (Danielsen 2006) taking into consideration the three basic and interdependent parameters for aggregate technology as shown in the knowledge triangle in Figure 2 (Danielsen 1987). Here the term "Aggregate Technology" may be applied for a combined use and interaction of the three essential fields of knowledge necessary in order to exploit, manufacture and use a mineral aggregate for a construction purpose:

- *Geology* – the geological basis for the materials, whether to be excavated from a sand/gravel pit or quarried in a hard rock location
- *Production technology* – the various equipment and methodologies available to transform the geological material into a well-processed building material
- *Materials technology* – the proportioning and use of the product material in order to meet the over-all requirements.

The characteristics of the geological material – mineral composition, structure and texture, crystal size, alterations, and – for a sand/gravel – the particle shape, grading, and surface properties, will be determinant both for product materials properties and for the choice of manufacturing processes.

There is interdependency between geology and production technology, as one and the same manufacturing process will not be suitable independently of the rock type and the quarry setting. Similarly, an optimum e.g. concrete proportioning will have to be adapted to the aggregate characteristics, given partly from the geological parameters, partly by the parameters determined from processing. And finally – the other way around – the requirements to the end-product in terms of e.g. mechanical properties and durability versus specific exposure conditions, will often be decisive for the choice of the geological raw material as well as for the production process to be designed.

As to local, geological conditions it may sometimes be relevant to consider typicality more than country when choosing a best available concept in a specific place of use. Most countries offer complex geological conditions (hard rock, weak rock, different rock types, sand/gravel sediments etc.), although some characteristic, regional differences do exist and must be taken into consideration, which has also to some extent been the basis for developing National methodologies and standards:

- Sand/gravel resources in the previously glaciated areas in the northern and alpine countries are primarily of glaciofluvial origin, opposite to the situation in central European countries where sand/gravel deposits are of fluvial type. And in some coastal North Sea regions sea dredged materials are most common. These three kinds of sediments are fundamentally different in their composition and also in their engineering properties.
- The large mountain ranges have provided some countries with an abundance of hard rock of many kinds, while a few countries like Denmark and Netherlands are totally dependent of importing such materials.
- Different relative distribution of sand/gravel and hard rock respectively have also resulted in the development of highly different application technology for aggregates in the concrete industry, where e.g. Spain can show a long term experience with crushed limestone aggregates, Norway and Sweden are developing crushed aggregate concrete with rock types a little more difficult for this purpose, and the sand rich regions have hardly needed such experience at all.
- When it comes to the production and use of recycled materials there is a similar, characteristic difference, but now mainly between densely and scarcely populated countries – depending on availability of natural resources, access to waste deposition areas, and the volume of structures being demolished. Clearly there is a great difference in local Best Practice between those who specify a recycled content in concrete (e.g. the Netherlands), those who prohibit it (e.g. Denmark) and those who intend to use it when the current situation makes it favourable.
- And finally, BAC in getting access to, opening and reclaiming a quarry will to a great extent depend on factors like population density, supply options and the local/regional need for materials – and thus differ a lot throughout Europe.

Somewhat simplified, the activities of the aggregate industry can be compiled into **four essential phases** (Danielsen 2007):

1) Inventory and planning,
2) Quarrying and production,
3) Use of aggregates in construction, and
4) Reclamation of mined-out areas.

Each of these phases will contain a number of sub-activities. Within each essential phase there will also be a set of environmental challenges and sustainability issues to be handled. Elements of BAC will have to be identified for each of these within the overall concept – to reduce environmental impact and to improve sustainability (table 1).

In many European countries, like in Norway, a key issue will be the management of resources. Natural sand/gravel (glaciofluvial or fluvial) is being rapidly depleted, and is a source of conflict regarding land use. In Norway, the most important precaution supported by research has been to gradually replace the natural sand/gravel with crushed (manufactured) aggregates. As can be seen from table 2, Norway is one of the European countries that has the highest percentage of crushed aggregates, 83 % in 2011 (Brown *et al.* 2013). A significant number of R&D and innovation projects have been conducted during the last 20 years to support such a change in technology (Wigum *et al.* 2009), and reference plants today can produce manufactured sand in qualities completely competitive with high quality natural sand.

Life cycle thinking and tools in the aggregate BAC

The production, supply and application of all types of aggregates lead to:

- Environmental impacts (e.g. GHG (Green Houses Gases) emissions, waste generation, consumption of resources)
- Social impacts (e.g. truck traffic)
- Economic impacts (e.g. through the consumption of water and energy)

Sustainable development is to some extent a compromise between environmental, economic and social goals of community, which allow present and future generations to live well. Understanding ecological limitations and clarifying possible risks allow making decisions.

On a project level sustainable construction involves both: assessing the potential environmental, social and financial impacts coming from the use of aggregates, and looking for the optimal triple bottom line solution to the sourcing and application of aggregates.

In order to convert specifications and standards from purely covering mechanical and technical properties to also take on board environmental and sustainability issues, some environmental and sustainability key parameters should be defined and declared, that will be decisive in future choice of aggregate sources and priority in a BAC:

- Carbon footprint from quarrying, production, transport and use
- The essential requirements in the CPD (regarding e.g. health, leaching)
- Technical properties (like today) – strength, abrasion resistance, durability
- Economic viability
- Mass balance and total utilisation (avoiding deposition of surplus)
- Resource management, plans for future land-use
- Pollution in production and transport (dust, noise, spill)
- Energy consumption in connection with quarrying, production, loading/handling, transport.

Taking these key parameters into consideration, the question in the future will likely have to be: how do we go about in structural and materials design to use the aggregate materials locally available with the lowest possible environmental impact? Instead of: where do we have to go to find and import materials complying with the pre-set technical requirements?

The gradual transfer to using crushed hard rock instead of sand/gravel has been mentioned. In city areas even sub-surface quarrying can be an alternative, and has already been tried in Norway for several years (Olsen 2013). Even though this initially has non-competitive cost levels, it has proven feasible when transport distances can be significantly reduced, and profitable future use of the mined-out volumes can be taken into consideration.

Another innovative approach to solve a potential transport problem was presented by Russian scientists some years ago (Harcenko *et al.* 2006). In the published case there was only fine grained sand available locally (Siberia), and coarse aggregate supply would have to rely on long-range transport, partly with helicopter. Instead, the scientists managed to develop a materials technology where concrete could be made solely by means of the fine sand aggregates.

A key element in approaching a BAC and standards focusing on sustainability will be novel development in LCA and LCC, resulting from a European project finishing autumn 2013 - CILECCTA (SINTEF 2013) and the set of indicators developed in another European project PANTURA (Thodesen & Kuznetsova 2013).

LCC is a tool that allows one to estimate the total cost of ownership of an asset over its lifecycle (Langton 2007). LCA is the methodology through which the lifecycle environmental impacts of an asset are determined quantitatively. By using LCA it is possible to make decisions based on potential environmental impacts by scoring and rating of environmental criteria (ISO 14040 2006). But many of these environmental factors cannot be quantified at all in cost terms. However, the European Union (EU) has put a price on carbon (EU 2013) in an effort to combat climate change; as a result it should be possible to incorporate the environmental costs over the lifetime of a project and to have a financial value to each tonne of emission saved.

The CILECCTA project (Life Cycle Costing and Assessment) has developed a bridge between life cycle thinking connected to both economics and the environment, and has created demonstration software based on this. The CILECCTA software combines the two methods, thus creating a new term:

Life Cycle Costing and Assessment (LCC+A). These calculations are based on not only investment costs, but also considering outlays on future maintenance or waste treatment, and neglecting the lifetime of the system components.

When we are talking about sustainable development, sustainability indicators, which have to measure processes of human and environmental systems, might be discussed (BS EN 15978 2011). Indicators are a useful tool used to simplify, determine in quantitative terms and summarize flows of information, and develop useful mechanism of feedback (ISO 21931-1 2010). As quantitative information, indicators can help to explain how specific concerns change over time.

Within the PANTURA project it was developed a set of indicators, benchmarks, monitoring methods and scoring criteria with which environmental disturbance of the direct vicinity of a construction site can be managed and reduced to acceptable level (Thodesen & Kuznetsova 2013). These indicator suites place emphasis on the disturbance aspects of an urban construction project and are composed of the following indicators allocated at different stages and also weights their relevance during the lifecycle of the project:

- Worker safety during construction
- Safety of residents
- Noise
- Mobility
- Total time of construction on site
- Reused or recycled materials
- Emission of greenhouse gases
- Generation of waste
- Total use of materials
- Life cycle costs
- Dust emissions

While these are indicators already well developed for buildings and infrastructure construction, they have so far been less focused for aggregate production and use. However, much of the systematic approach and issues should be just as applicable and relevant also in the aggregate sector. The tools developed and tried in these two projects will be valuable in establishing new methodologies for valuating aggregate sources, prioritising production alternatives and make the design for use from a sustainability point of view.

Conclusions and recommendations

Future actions and research on mineral/aggregate resources for the building/construction industry should aim at three important areas of priority, in making up the essentials of a BAC:

1) Tools for mineral resource management,
2) Concepts and technologies for optimum production and use of aggregates, and
3) Development of new or revised specifications and standards that highlight and prioritise environmental/ sustainability issues.

Resource management

Conflicts due to land use for quarrying are common all over Europe and the need for long term planning is a pressing social, economic and political issue.

There is little doubt that future exploitation of mineral resources will play an important role in the economy of European countries, but there are important threats to this development, and critical weaknesses in the European management of such resources:

- Important mineral resource areas are under pressure from other land use; the future mineral potential in Europe must be put on the map.
- There is a general lack of knowledge in the society concerning the importance of mineral resources to a modern society.
- There is a lack of mutual understanding of land use management measures for mineral resources.
- There is a lack of integration between management levels, particularly involving the local communities and land owners.
- No appropriate tools exist to classify and predict the value – in a broad sense; technical, economic and environmental – and importance of mineral resources on a short and long term.
- Mineral resource databases must be integrated with other spatial datasets on land use planning.

Optimum production and use

An urgent need, and a major challenge will be to comply with increasing requirements and expectations concerning sustainability and environmental profile, while at the same time keeping up a cost effective and profitable production and meeting the relevant technical requirements.

The future potential in development of production and use could be connected with:

- Concepts and technology to make crushed (manufactured) aggregates (including the sand sizes) economically and technically competitive with natural sand/gravel aggregates, and this technology broadly implemented.
- Technology that could take better advantage of specific rock types to obtain specific (designed) materials properties.
- Technology to enable the utilisation of (traditionally) secondary aggregates and/or marginal sources, in order to lessen the pressure on precious resources – structural and materials design that utilise available aggregates, not just searching for the "ideal" ones.
- Concepts to constantly obtain 100% mass balance, including areas of use for the surplus fines, thus avoiding any waste deposits of excess sizes.
- Concepts to utilise local aggregates and avoid excess transport and pollution.
- Integrated plant concepts that reduce materials transport and make the down-stream production more efficient and environmentally friendly.
- More economically feasible sub-surface plants, in combination with the establishment of underground construction in urban areas.

Applying life cycle concepts for new methodologies and standards

Traditional resources are getting rapidly depleted at the same time as their need is increasing, the environmental awareness gets more pronounced along with the increasing constraints against encroaches upon nature. This situation calls for these three priorities being focused simultaneously. Novel developments in LCA/LCC concepts can be very useful tools in combination with knowledge of geology, materials technology and processing in order to come up with Best Available Concepts, which could materialize in more holistic standards and specification, combining technical and environmental considerations.

Systemic approach to a BAC

Figure 3 finally intends to present a summary of the approach which was discussed above and recommended for a BAC in aggregate business and research. The core of this BAC will be the competence triangle for aggregate technology (geology, production and user technology). This combined competence will be needed to handle the four stages in aggregate processing (inventory and planning, quarrying and production, use in construction, reclamation – as developed in table 1) and the five key issues of sustainability (mineral resources, land-use, mass balance, energy use and emissions) – and channel these through the available knowledge of LCC/LCA to produce the final solution in a given case.

References

Bleischwitz, R. & Bahn-Walkowiak, B. 2006. *Sustainable Development in the European Aggregate Industry – a Case for Sectorial Strategy.* 2006 Berlin Conference on the Human Dimensions of Global Environmental Change.

Bloodworth, A.J., Scott, P.W. & McEvoy, F.M. 2009. Digging the backyard; Mining and quarrying in the UK and their impact on future land use. In: *Land use policy*. Elsevier.

Brown, T.J., Hobbs, S.F., Mills, A.J., Peravratzi, E., Raycraft, E.R., Shaw, R.A. & Bide, T. 2013. *European Mineral Statistics 2007-2011. A product of the World Mineral Statistics database.* British Geological Survey.

BS EN 15978. 2011. *Sustainability of construction works. Assessment of environmental performance of buildings. Calculation method.* BSI.

Cepuritis, R. 2014. New type of crushed sand to replace natural sand in concrete production. *Results Minerals & Aggregates*. Metso's customer magazine for the mining and construction industries, **2**.

Dahl, R. & Eriksen, E. 2013. *A new valorization system for geological building materials of national, regional and local significance*. Geological Society of Norway. Winter meeting 2013, Oslo.

Danielsen, S.W. 1987. *Optimising aggregate properties for high strength concrete*. Proc. Int. Symp. High Strength Concrete, Stavanger, 73-87.

Danielsen, S.W. & Ørbog, A. 2000. Sustainable Use of Aggregate Resources through Manufactured Sand Technology. *Quarry Management.* July 2000, **27(7)**, 19-28.

Danielsen, S.W., Hólmgeirsdóttir, Þ., Mathiesen, D., Muhr, T., Nielsen, C.V., Sveinsdottir, E-L. & Wigum, B.J. 2004. Baseline Report for the Aggregate and Concrete Industries in Europe. *In: ECO-SERVE Network, Cluster 3: Aggregate and Concrete Production.*

Danielsen, S.W. 2006. A Best Available Concept for the Production and Use of Aggregates. *Proc. Challenges for Sustainable Construction: The Concrete Approach.* EcoServe seminar, Warsaw, Poland, 135-142.

Danielsen, S.W., Gränne, F., Hólmgeirsdóttir, Þ., Jonsson, G., Krage, G., Mathiesen, D., Nielsen, C.V. & Wigum, B.J. 2006. Best Available Technology Report for the Aggregate and Concrete Industries in Europe. *In: ECO-SERVE Network, Cluster 3: Aggregate and Concrete Production.*

Danielsen, S.W. 2007. Sustainability in the production and use of concrete aggregates. *Proc. International Conference on Sustainability in the Cement and Concrete Industry.* Lillehammer, 322-333.

EUAA (European Aggregate Association) (2011) *Sustainable Development in the European Aggregate Industry – For the Benefit for Future Generations.* Position paper. UEPG

European Commission. 1989. *The Construction Products Directive 89/106/EEC*. European Parliament, Brussels.

European Union. 2013. *The EU Emissions Trading System (EU ETS).*

EUROSTAT 2003. The Lucas Survey – European statisticians monitor territory. Updated edition June 2003, Luxembourg, European Commission, Office for Official Publications of the European Communities.

Harcenko, I., Pantchenko, A., Stark, J. & Fisher, H.-B. 2006. *Sandbeton für monolithischen Häuserbau am Polarkreis*. Tagungsbericht 16. Internationale Baustofftagung Weimar, Sept. 1-0033 – 0045.

Hammond, G.P. & Jones, C.I. 2008. Embodied energy and carbon in construction materials. *Proceedings of the Institution of Civil Engineers - Energy,* **161 (2)**, 87-98.

ISO 14040. 2006. *Environmental management—life cycle assessment—principles and framework.* ISO, Brussels.

ISO 21931-1. 2010. *Sustainability in building construction - Framework for methods of assessment for environmental performance of construction works. Part 1: Buildings.* ISO, Brussels.

Langdon, D. 2007. *Life cycle costing (LCC) as a contribution to sustainable construction: A common methodology*. Final Report. David Langton Management consulting.

Langer, H., Drew, J. & Sachs, J.S. 2004. *Aggregates and the Environment.* American Geological Institute.

Langer, W. 2009. *Sustainability of aggregates in construction. In:* Khatib, J. M. (ed.) *Sustainability of construction materials.* Chapter 1. Woodhead Publishing Limited.

Neeb, P-R. 2013. *Norway's coastal aggregates. Export in 2012 and potential.* Geological Survey of Norway, Report no.: 2013.036, ISSN 0800-3416.

Olsen, V. 2013. *The quarry industry of the future – methods for effective sub-surface quarrying of construction aggregates* (In Norwegian). Presentation given at the annual conference for the mining and quarrying industry, Trondheim, Norway.

SINTEF (ed. on behalf of project partners). 2013. *Sustainability within the Construction Sector – CILECCTA – Life Cycle Costing and Assessment*. E-handbook summarising EU project CILECCTA. SINTEF Academic Press. ISBN 978-82-536-1343-7.

Smith, R.A., Kersey, J.R. & Griffiths, P.J. 2002. *The Construction Industry Mass Balance; Resource Use, Wastes and Emissions.* Virdis Report ISSN 1478-0143.

Šolar, S., Shields, D., Langer, W.H. 2004. Important features of sustainable aggregate management. Geologija, Ljubljana, **47/1**, 99-108.

Šolar, S., Shields, D., Zelič, U. 2012. Sustainable Aggregates Resource Management: experience learnt and shared within South East Europe. *RMZ – Materials and Geoenvironment.* **59 (2/3)**, 181–200.

Thodesen, C.C, Kuznetsova, E. 2013. *Proposed new measures and standards on health, safety, sustainability and structural reliability*. Report within EU project PANTURA, Delivery 6.21, SINTEF, Trondheim, Norway.

Wellmer, F. W. & Becker-Platen, J. D. 2002. Sustainable development and exploitation of mineral and energy resources: A review. *International Journal of Earth Sciences*, **91**, 723–745.

Wigum, B. J., Holmgeirsdottir, T., Danielsen, S. W. & Andersen, O. V. 2004. *Production and Utilisation of Manufactured Sand for Concrete Purposes*. Report Hønnun, Iceland.

Wigum, B. J., Danielsen, S. W., Hotvedt, O. & Pedersen, B. 2009. *COIN – Production and utilisation of manufactured sand, state-of-the-art report*. Report within research project COIN, SINTEF *et al.* Trondheim, Norway.

Willis, K. G. & Garrod, G. D. 1999. Externalities from Extraction of Aggregates – Regulation by Tax or Land-Use Controls. *In: Resource Policy*, Pergamon, 77-86.

Figures

Fig. 1: Norwegian aggregate export 2011 according to NGU (Dahl & Eriksen 2013)

Fig. 2: The principles of Aggregate technology (Danielsen 1987)

Fig. 3: A BAC (Best Available Concept) for aggregate production and use

Tables

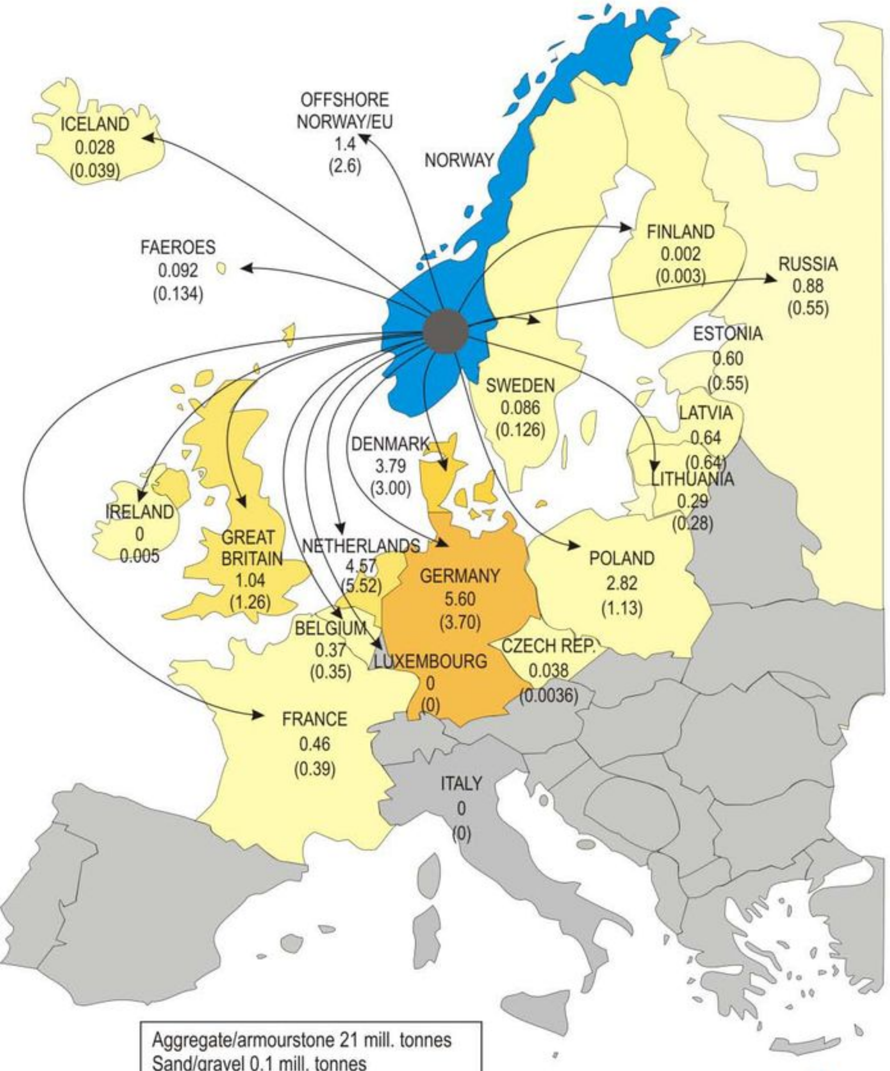
Table 1: Four essential phases in aggregate business, sustainability issues and BAC

Table 2: European aggregate production (based on Mineral Statistics) (Brown *et al.* 2013)

NORWEGIAN AGGREGATE EXPORTED IN 2011

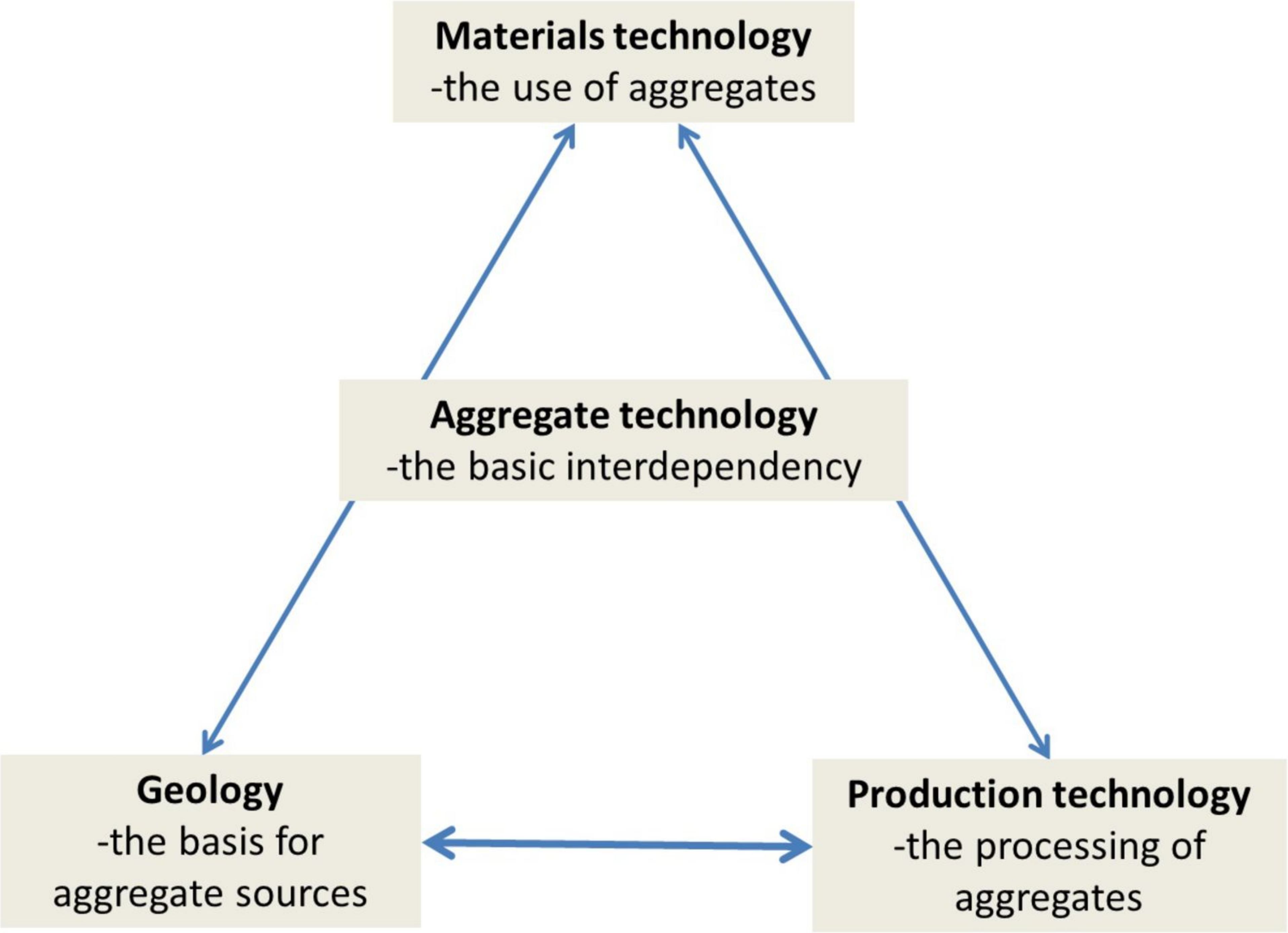
Total production export 21 mill. tonnes aggregate, armourstone, sand and gravel, plus 1.4 mill. tonnes aggregate for offshore use.

Exportproduction values for 2010 in parentheses .



Aggregate/armourstone 21 mill. tonnes
Sand/gravel 0.1 mill. tonnes
Export value 1009 mill. NOK/126 mill. EUR
Offshore-aggregate 1.4 mill. tonnes

NGU
Norges geologiske undersøkelse
Geological Survey of Norway


Materials technology
-the use of aggregates
Aggregate technology
-the basic interdependency
Geology
-the basis for aggregate sources
Production technology
-the processing of aggregates

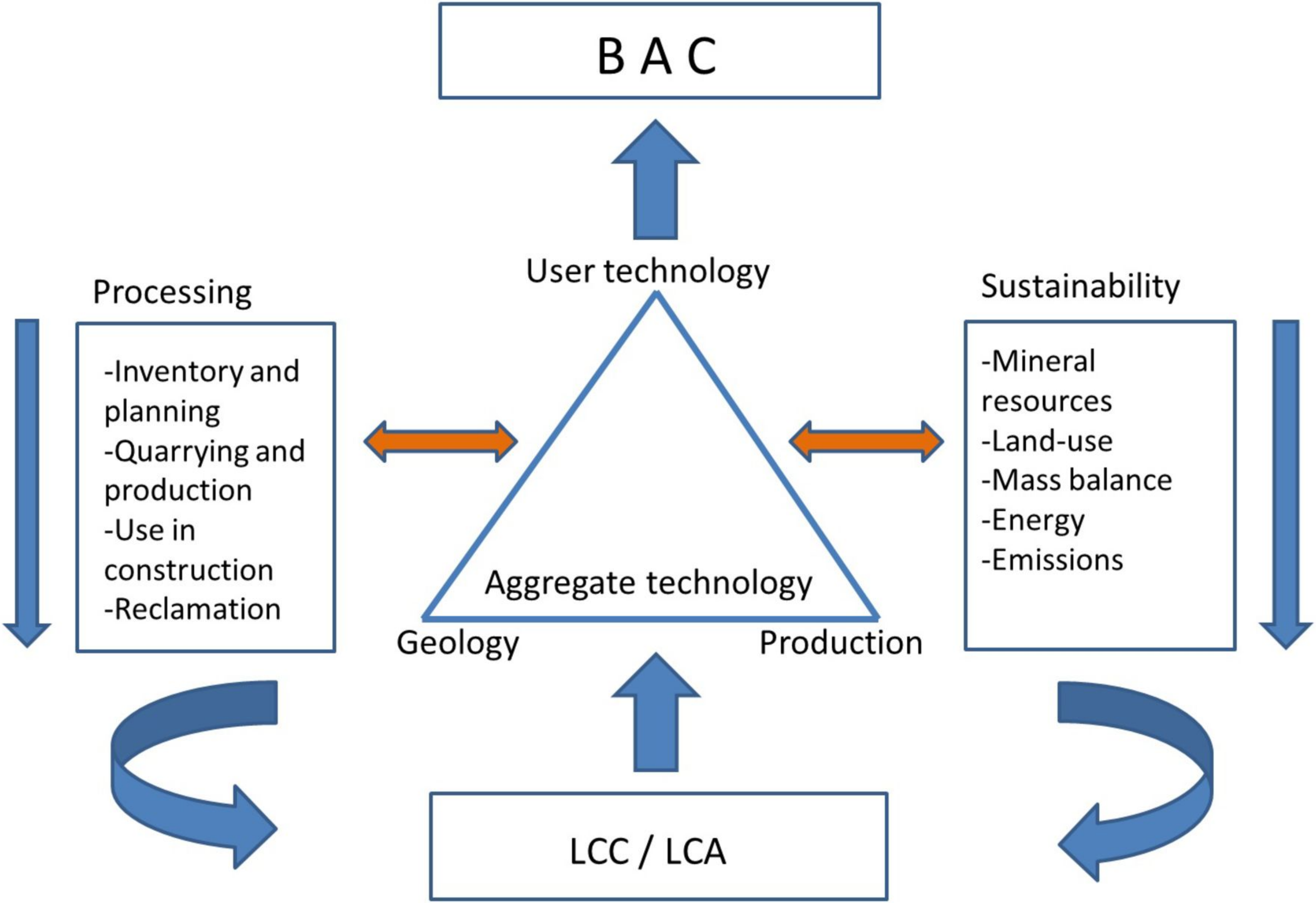

B A C
User technology
Processing
-Inventory and planning
-Quarrying and production
-Use in construction
-Reclamation
Sustainability
-Mineral resources
-Land-use
-Mass balance
-Energy
-Emissions
Aggregate technology
Geology
Production
LCC / LCA

Table 1. *Four essential phases in aggregate business, sustainability issues and BAC*

	Inventory and planning	**Quarrying and production**	**Use of aggregates in construction**	**Reclamation of mined-out area**
Processes	Geological mapping Regulatory issues Planning of exploration and quarrying Planning of future reclamation	Extraction Handling and transport Production Storing Waste depositing	Most aggregate volumes are used in road pavements and concrete – sub-activities: Performance analysis Quality control Materials proportioning	Plans for reclamation will be vital to obtain quarrying permits. Activities: Regulatory work Investigate to preserve biological habitat Restoration, remove pollution Establish new area for use – shape the landscape Establish vegetation zones Secure the area – physical safety
Key environmental issues	Geology and access to resources – aggregates can only be extracted where nature has placed them --> environmental conflicts regarding nature, neighbourhood, transport	Potential impacts considered: Dust, noise, vibration Truck traffic near operations Visually and physically disturbed landscape and habitats Affected surface and/or groundwater	Products in accordance with essential requirements (CPD) – health effects, leaching of chemicals Chemical and physical durability will affect long term materials consumption and structural safety	Pollution and waste control Avoid left-over of waste deposits, storage tanks and polluted soil Control drainage and groundwater conditions
Issues of sustainability	Any encroach upon nature should be justified by increased value for society, materials produced should meet essential requirements	Mass balance will be a key Logistics Energy consumption	A use that saves resources and minimizes waste generation/ depositing, needs a minimum of energy consumption, and gives a maximum of added value	Establish long-term/permanent solutions. Create sustainable value for society – a balance of industrial, environmental and societal priorities Quarries will always be temporary
Elements of BAC	Identify resources Identify conflicts Provide vital info for planning for availability Identify future options as to reclamation Identify means for reducing environmental impact Locate quarry to avoid visibility and earn neighbourhood acceptance	Technology to prevent/reduce pollution in quarrying Novel crushing and sorting technology to improve mass balance Market actions to avoid un-balanced sales Integrated plants with on-site down-stream solutions to avoid excess mass transport	Investigate local options: Available resources Possibilities to replace sand/gravel with crushed or recycled material Consider design requirements, avoid too strict and narrow requirements to be able to use broader sizes Apply newest standards and novel application technology	Reclamation calls for interdisciplinary planning, decision-making and engineering, securing finances for reclamation activities. Provide essential data for implementing reclamation Obtain broad ownership to the chosen solution among stakeholders Utilise a broad co-operation between disciplines and parties involved to ensure optimum solutions

Table 2. *European aggregate production (based on Mineral Statistics) (Brown et al. 2013)*

Total production		Share of crushed aggregates	
Mill.tonnes	Country	% crushed	Country
482	Germany	100	Cyprus
357	France	87	Portugal
259	Poland	85	Belgium
242	Italy	**83**	**Norway**
182	Spain	78	Ireland
165	UK	77	Sweden
77	**Norway**	75	Finland
74	Sweden	71	Spain
64	Finland	64	Estonia
63	Austria	64	Czeck rep
58	Czeck rep	63	Bulgaria
53	Portugal	63	Slovakia
52	Belgium	62	UK
45	Switzerland	57	France
40	Netherlands	48	Germany
36	Hungary	47	Slovenia
32	Ireland	44	Lithuania
31	Romania	43	Austria
27	Bulgaria	32	Poland
21	Slovenia	32	Italy
16	Slovakia	31	Hungary
12	Cyprus	26	Denmark
11	Estonia	22	Latvia
10	Lithuania	19	Romania
10	Latvia	11	Switzerland
5	Croatia	0	Croatia
2	Denmark	0	Netherlands
2425	**TOTAL**	52	**TOTAL**