european cement research academy

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Technical Report

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Future Grinding Technologies - Report about Phase 1: Evaluation of Roundtable Event

ECRA Future Grinding Technologies Project – Report about Phase I

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1 Executive summary

In 2014 the European Cement Research Academy (ECRA) has started the cross sectorial "Future Grinding Technologies" research project in order to optimize and develop comminution technology for the cement industry but also for other related sectors. With today´s and tomorrow´s challenges regarding energy- and resource-efficiency in mind grinding within the cement industry has to be rethought. New concepts and technological approaches towards efficient comminution are required.

In order to build up a cross-sectorial research community for the first phase, a Roundtable event was held in November 2014. It was open to all researchers in the field of comminution and grinding experts from the cement industries as well as other industries. Next to lectures and plenary discussions three workshops were conducted with themes ranging from the machine-level (micro) with definition of all its sub-functions up to the more abstract industry-level (macro) to collect synergies between the cement industry and other comminuting industries

The discussion and the results of the working groups have shown that the control of product properties along with the flexibility of production are as important as energy efficiency. Furthermore the need to reduce OPEX short term without high CAPEX was stressed throughout the discussions. This was furthermore confirmed by more detailed evaluations during the workshop phase. Summarized beneath the topic "quality" the control of the particle size distribution (PSD) and tools for a-priori determination of changes in the PSD have been discussed intensively. Cement properties especially water demand and strength development are strongly depending on the PSD but also the control of surfaces plays an important role.

The working groups of the Roundtable event achieved largely intersecting results, despite of its generally independent conduct. Discussions in all working groups automatically led to very common basic points. Also outside the cement industry the main challenges are the same: Quality and energy. Since fineness of materials is playing a very important role both for quality and energy efficiency it has to be investigated what possibilities for limiting fineness by a product-based approach are available. For the cement industry this would involve a closer look at the cement's use in concrete and at today's standards. It has to be noted that in order to not limit the possible outcomes directly at the beginning CAPEX, although of significant importance, was widely excluded from the workshop discussion. Synergies between the cement industry and other comminuting industries can be found especially regarding basic theoretical knowledge and sub-processes like material transport. Improvement of knowledge can result in more efficient, stable and inexpensive grinding processes in the cement industry and also in similar industries

A systematic improvement of the comminution process starts with the benchmarking of existing equipment including all auxiliaries. This task involves the reliable determination of the processes impact on product properties, especially PSD. Therefore the application of comminution models for reliable prediction of the particle size distribution has to be tested and results have to be validated. Models then can be used to benchmark even non-traditional grinding equipment and to derive new technological approaches. Furthermore the modelling of the process along with better and reliable test procedures for characterization of the materials will allow controlling particle size distribution in the given equipment better and can lead to new operation and control concepts. In order to obtain results that can be applied universally developed tools have be designed flexible.

Basic modelling approaches required for benchmarking and long term research activities can directly lead to results of high practical relevance. These can be used for optimization of existing grinding plants (e.g. ball charge grading in ball mills). This can short-term improve troughput, efficiency, reliability, wear rates and other important factors. In a second step results can be applied to the developed database on comminution technology in order to allow the develepement for optimum plant layouts using given technology. The final phase of the research project can than focus on the actual development of new future grinding technologies ready for tomorrows requirements on comminution.

2 Introduction

The European Cement Research Academy (ECRA) has decided to broaden its research activities and to set a new focus on "Future Grinding Technologies". In June 2014 ECRA's Technical Advisory Board set a new respective research project in order to improve grinding and comminution in the context of a sustainable, energy- and resource-efficient cement production.

As **Figure 2-1** shows between 60% and depending on cement properties up to 70% of the roughly 100 - 110 kWh per ton of cement are used for comminution processes while also being of greatest importance for the final product quality [GNR, 2015][VDZ, 2015]. With todays and tomorrows challenges regarding energy- and resource-efficiency in mind grinding within the cement industry should be rethought. New concepts and technological approaches towards efficient comminution are required.

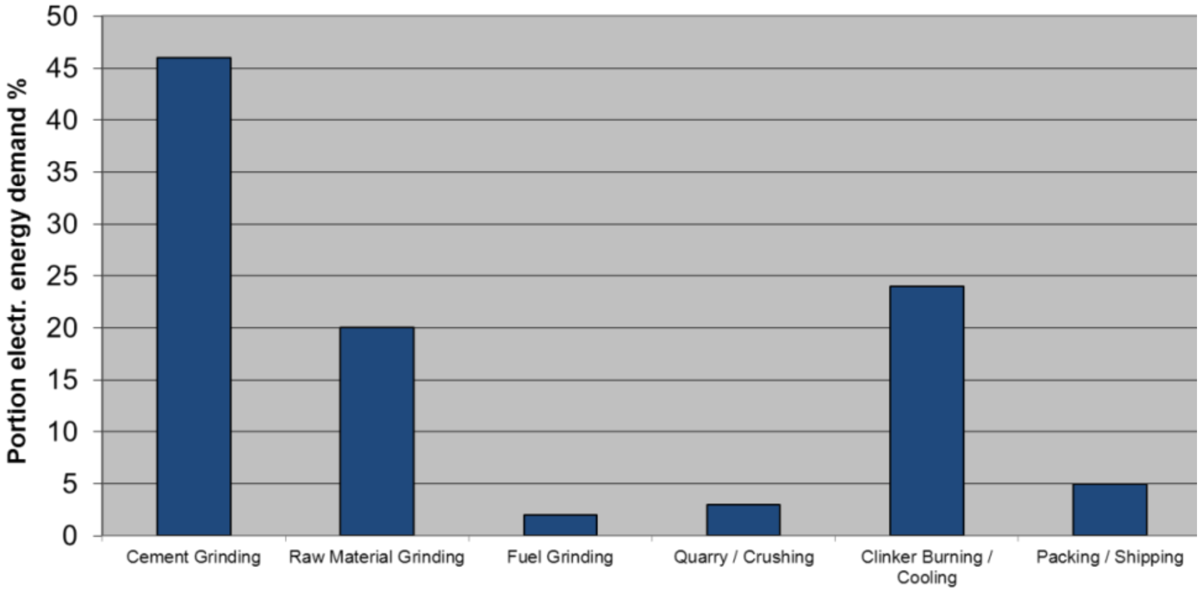


Figure 2-1 Portion of electrical energy demand for cement production. [FLE, 2014]

ECRA has taken on this challenge and set up a research project dealing with efficient grinding in the cement industry. The project is precompetitive and will look at future grinding technologies for the cement manufacturing process. In order to draw benefit from experience in other sectors the general approach is cross-sectorial.

The project is open to interested experts from the cement industry, technology suppliers, researchers and comminution experts form related industries and universities. In order to build up a cross-sectorial research community and to define and present the project's aims and the approaches for the first phase the Roundtable event was held in November 2014. It was open to all researchers in the field of comminution and grinding experts from the cement industries as well as other industries

Based on literature studies and the results gathered during the Roundtable a proposal for a research agenda including various work packages was developed. The present report summarizes the results of Phase 1 and defines the possible next steps of the project.

3 Industrial grinding technology in the cement industry

Cement is a hydraulic binder produced by grinding of cement clinker and other constituents like granulated blast furnace slag (GBFS), pozzolana, limestone or fly ash. Raw material is quarried, crushed and homogenized. The raw mix is then dried and ground in the raw mill before fed to the kiln as powder with R90µm of approx. 10 to 15%. The efficiency and quality of the clinker burning process strongly depends on the homogeneity and fineness of the raw meal. The finished clinker is ground in cement mills separately or together with other main constituents in order to produce the final product. The cement is then stored in silos or directly prepared for shipping (see **Figure 3-1**). Fineness and particle size along with the chemical and mineralogical composition are main drivers for the final product properties and therefore of highest importance for product quality.

The comminution processes cover coarse size-reduction by crushing as well as fine grinding with interesting size fractions in the range of 3 to 32 µm. All comminution processes (with very few raw material dependent exceptions) in the cement industry are operated dry. Typical capacities for raw material grinding range from 300 - 1000 t/h and for cement grinding from 50 - 250 t/h while larger installations up to 450 t/h are possible.

With regard to total energy demand crushing and fuel grinding is of minor importance. While in some markets a shift towards use of coal and petcoke as primary fuel is taking place others are utilizing more and more alternative fuels such as RDF (residue derived fuel). Comminution along with drying of alternative fuels is becoming interesting with increasing substitution rates but until now only very few installations have been reported.

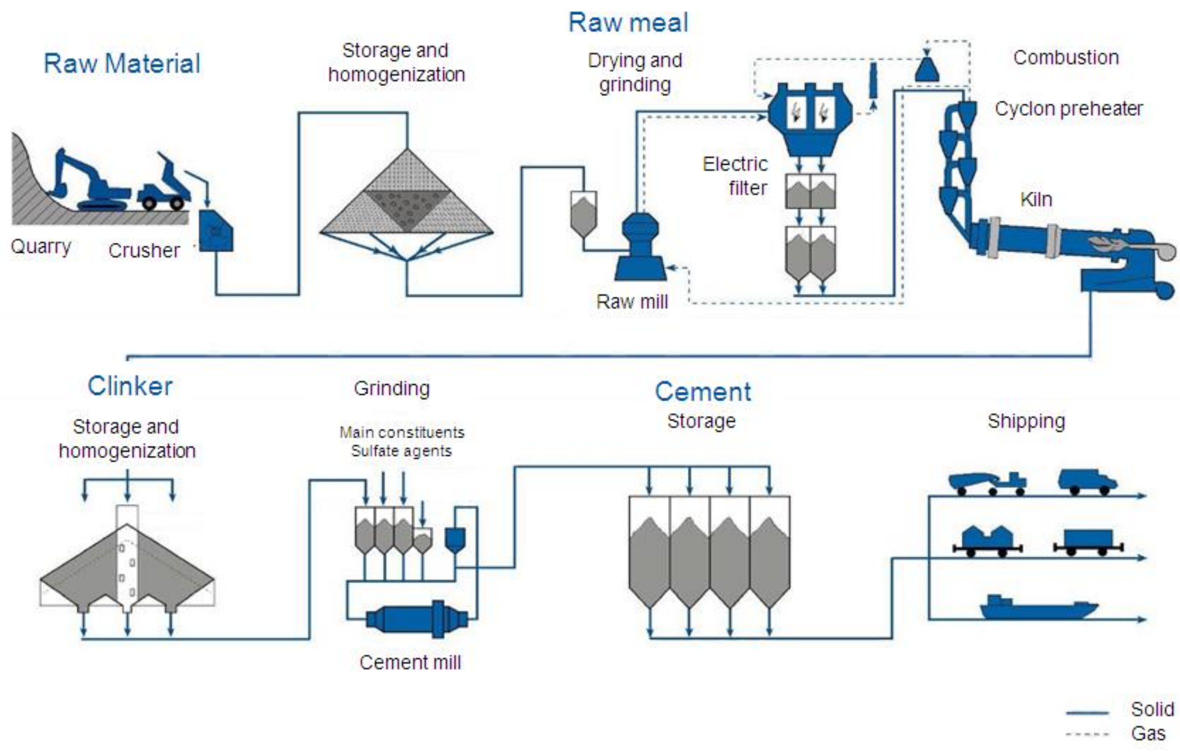


Figure 3-1 Flow sheet of cement production. [VDZ, 2008]

3.1 Main constituents of cement

Cement properties (esp. compressive strength) are depending to a large extent on the reactivity of the constituents. Ordinary Portland Cement (OPC or CEM I) consists to over 95% of clinker while other cement types like composite cements, blastfurnace cements or pozzolanic cements consist of different portions of the other constituents.

At least two thirds of the cement clinker consists of two calcium silicates, namely tri- and di-calcium silicate, which are richest in CaO and can react with the mixing water and harden reasonably rapidly. It is therefore a hydraulic substance [LOC, 2006].

The other cement main constituents besides clinker can be ordered into three groups:

- Latend hydraulic materials (e.g. Granulated Blast Furnace Slag)
- Pozzalanic materials (e.g. fly ash, trass or activated clays)
- Inert materials (e.g. limestone)

Clinker with its relatively high hydraulic reactivity reacts early and is in any case very important for the early strength development of the cements. Granulated blast furnace slag (GBFS) with its latent hydraulic properties reacts later and benefits mainly the late strength development similar to constituents with puzzolanic properties. Inert materials like limestone are used as filling material to improve the physical properties. Especially the substitution of clinker by limestone is very interesting since it is in general available in large amounts on site. But since it does not feature hydraulic properties, replacement of high amounts of clinker in particle size areas which are responsible for the strength development could decrease the performance of the cement.

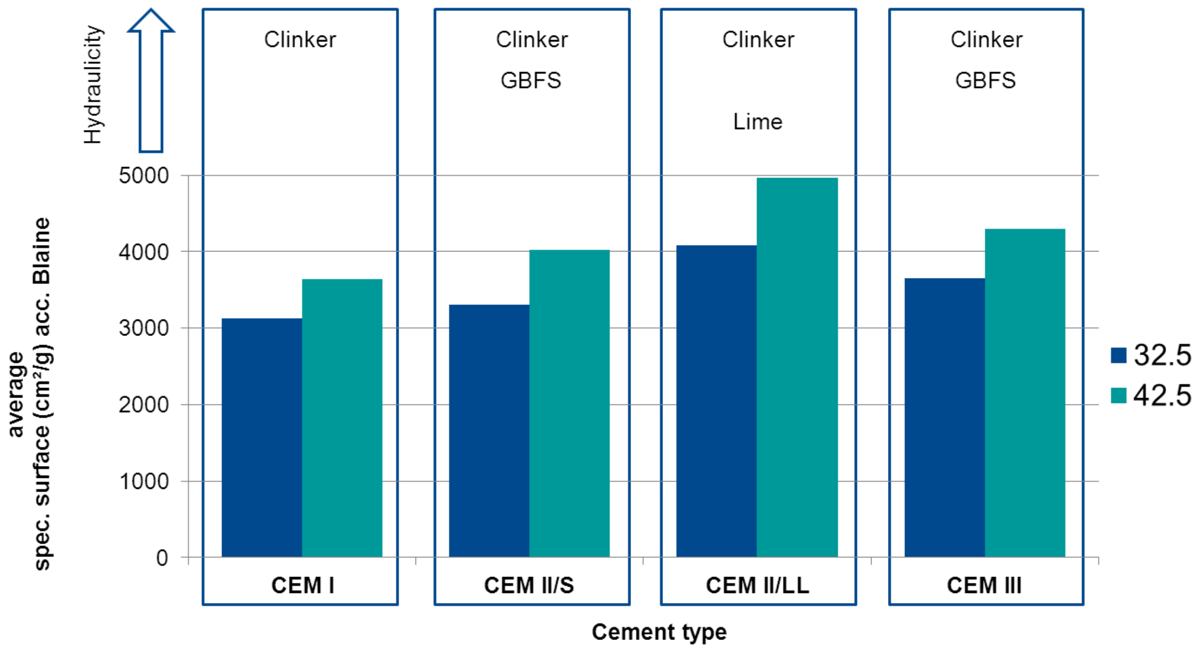


Figure 3-2 Average product fineness depending on cement type, hydraulicity of the constituents and strength class.

By replacing clinker by other main constituents CO_2 emissions from cement produtin can be reduced. According to the grindability of the materials used the efficiency of the total grinding process can increase or decrease. While limestone in general features a very low grindability, slag is harder to grind than clinker. But even limestone can be difficult to grind because of its stickyness and coating behaviour. As can be seen in **Figure 3-2** the average fineness depends on the constituents and increases with decreasing clinker portion.

Limestone is usually ground to high fineness and takes influence on the physical properties of fresh mortar and fresh cement. The improvement of the product properties is (theoretically) possible by manipulation of the particle size distribution and distribution of all main constituents among certain fractions within the particle size distribution.

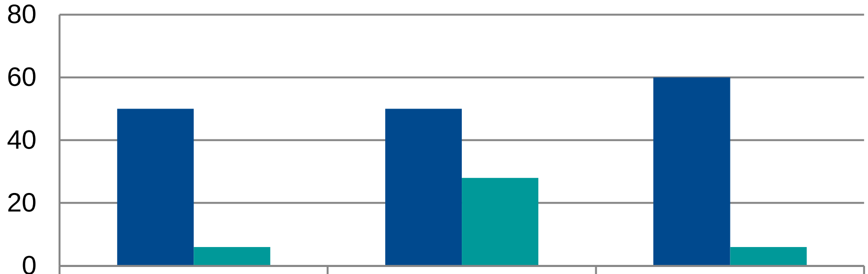
3.2 Equipment for cement grinding

For the grinding processes in cement manufacture today several techniques are in use, which have been developed over years. The oldest of the industrially sized grinding technologies is the ball mill, which has been used since the 19th century. The major reason for adhering to this grinding technology for such a long time is its well-known robustness and reliability. With the ball mill it is possible to produce a wide particle size distribution (PSD), which is necessary for good workability of the fresh mortar and the fresh concrete. But there is also a downside to the great variability of the mill. The ball mill has a relatively high specific energy demand per ton of product. Only a very small portion of the electrical energy is converted into grinding work. The rest is dissipated in the form of heat and sound. Nevertheless, in Europe more than 60% of the grinding plants for cement production are equipped with ball mills, because of the positive effects on cement achieved with this comminution technology.

The vertical roller mill (VRM) was initially used mainly for raw meal grinding because of the very good drying capacity (see **Figure 3-3**) but is today found in many new cement grinding installations. The most important criterion for this development is the specific energy demand, which is up to 40% lower compared to that of a ball mill. The PSD generated by this type of mill, when used for cement grinding, is comparably narrow. This can lead to higher water demand. Compared to other parts of the world in the region of Europe still fewer installations can be found for cement grinding.

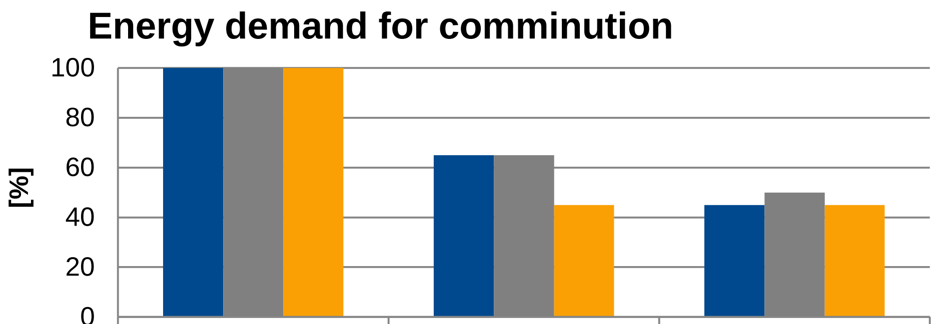
The high pressure grinding rolls (HPGR) were developed in the 1990s. Like VRM it also belongs to the group of high pressure grinding mills and features much lower energy consumption for grinding. It is a cost efficient possibility to increase the production of many existing ball mill grinding processes, as long as the initial material moisture is not too high. The HPGR has an even stronger impact on the PSD than the VRM. Therefore it is almost exclusively used in combination with a ball mill for the final adaption of the PSD. The horizontal roller mill (Horomill) has also been used in the cement industry for about 20 years. With respect to the specific energy demand and the product quality, the characteristics of this mill type are similar to those of the roller press.

As **Figure 3-4** shows, the high pressure grinding equipment features a significantly lower specific energy demand compared to the ball mill. For finish grinding of cement depending on the product 30-35% less energy is required. Finish grinding only on the HPGR can be realized with up to 50% less energy but leads to very narrow size distributions. In combination with a ball mill the overall energy demand is very similar to the VRM.



	Ball mill	VRM	HPGR
Max. feed size [mm]	50	50	60
Max. moisture [%]	6	28	6

Figure 3-3 Exemplary comparison of the maximum feed size, product size and maximum feed moisture between ball mill, vertical roller mill and high-pressure grinding rolls.



	Ball mill	VRM	HPGR
Raw meal	100	65	45
OPC (~4000 Blaine)	100	65	50
Slag (~4500 Blaine)	100	45	45

Figure 3-4 Exemplary comparison of the energy demand in per cent to comminute different materials in the ball mill, vertical roller mill and high-pressure grinding rolls.

3.3 Classifiers

Fine products can normally only be produced by separating the fine (finest) material from the grinding circuit. In general the efficiency of the grinding plant can be improved by using classifiers. Since dry fine separation in most cases cannot be realized by screens air flow separators are used. These systems are capable to handle the typical industrial throughputs.

In the cement industry air flow separators are generally used to:

- Remove fine material of sufficient fineness from the grinding circuit,
- Avoid agglomeration and damping effects in the mill and in this way,
- Improve energy efficiency during grinding,
- Produce finished products with a defined upper particle size.

The efficiency of the separation process is affected by the type of equipment as well as by the operating parameters. Modern classifiers allow the control of product properties to a certain extent. But in most cases the higher the efficiency of a separator is, the narrower is its product particle size distribution. This in turn influences the cement properties. Most commonly used separators in the cement industry are:

- Static classifiers:
    - Static air classifier (first generation) – used in air swept ball mills for raw material and coal grinding
    - V-separators – used in combination with HPGR
- Dynamic classifiers:
    - Recirculating air classifier or rotary air classifier (second generation)
    - Cyclone recirculating air classifier (second generation)
    - Caged rotor classifier (high-efficiency classifier) (third generation)

The main difference between these systems is the possibility to adjust the fineness by alteration of the speed of revolution of an additional rotor or cage. Product properties are thus much easier to control. In static separators during operation only the airflow produced by a fan can be used to affect the cut size. In some designs it is also possible to dry or cool the material in the classifier.

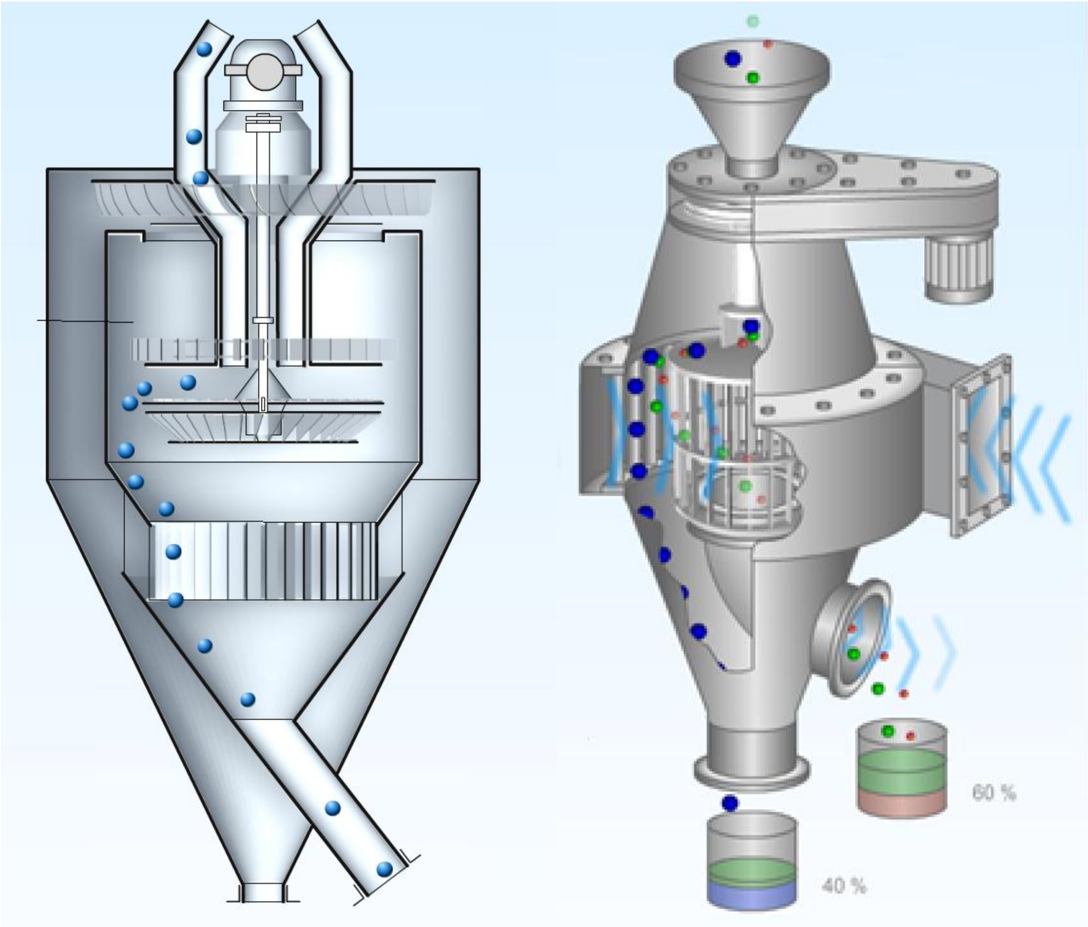


Figure 3-5 Visualization of a classifier of the second generation (left) and the third generation (right)

Besides an optimized energy transfer and particle stress the minimization of ready ground product particles in the comminution zone is a requirement for optimized grinding operation. Furthermore PSD and by this product quality are controlled by the classifier. Therefore it is necessary to fully include classification processes in the scope of the ECRA project.

3.4 Auxiliaries in the cement grinding process

Considering the overall efficiency of the grinding process it is necessary evaluate all auxiliaries as well. These can impact the efficiency of the cement grinding process significantly. Therefore it is important to evaluate the influence of these units on the entire grinding process and take into account the full plant design for the development of a benchmark approach. Most important auxiliaries in cement grinding are:

- Fans
- Transport
  - Air conveying
  - Bucket elevator
  - Belt conveyor
- Blending and storage
- Cement cooler

The efficiency of a grinding plant is depending mainly on the grinding principle. Energy demand of auxiliaries can decrease efficiency of the plant. Therefore efficiency of grinding plants with modern comminution equipment can decrease to a level below traditional ball mill circuits due to energy demand of its auxiliaries [FLA, 2015]. This of course has to be evaluated against the background of the product portfolio and the requirements on flexible production.

3.5 Current market development

Huge challenges with regard to increasing energy costs have initiated substitution of existing grinding equipment by new mills. However, in most cases such substitution is not economical based only on energy savings. Therefore it has to go along with an increase or pooling of production capacity [AUX, 2009].

While vertical roller mills (VRMs) are predominantly used for raw material grinding, different types of grinding systems are used for finish grinding of cement. VRMs are well established, however, HPGRs in conjunction with ball mills are also widely used. In any case, finish grinding operations containing ball mills are still frequently found on global level. Outside of China the VRM is way ahead with 113 mills ordered in 2012 followed by 51 ball mills and high-pressure grinding rolls (HPGR) (**Figure 3-6**) [HAR, 2013]. Latest global technological trends do reflect these developments: Most new equipment concepts are focusing on VRMs and their drive units [ERI, 2013] [SCH, 2013b] [STR, 2013b] [SCH, 2014]. But with 460 new mill orders in 2012 China's local market is way above the rest of the world. With over 60% in

China the majority of cement is produced on grinding systems with HPGRs [WEI, 2013] [HAR, 2013].

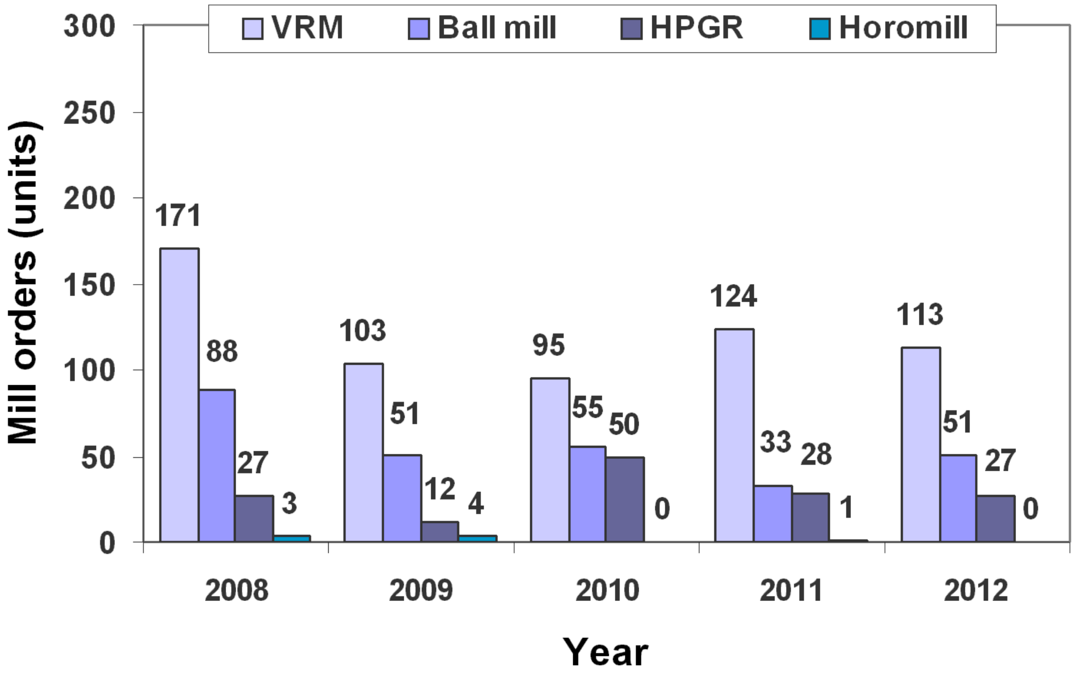


Figure 3-6 Mill types ordered from 2008 till 2012. Local supply in China excluded from figures. [HAR, 2013]

During the last years a development towards larger "one-mill" grinding installations has been observed. Currently the capacity of the largest installations ranges around 550 t/h for cement grinding and up to 1400 t/h for raw material grinding. VRM table diameters reach up to nearly 7 m and installed power to 13.000 kW [REI, 2010] [STR, 2013] [FLS, 2015]. Drive concepts have underwent further development respectively.

Due to the robustness of the system on one hand and the typical wide PSD of the final product on the other hand there are also new installations of ball mills. Furthermore it has to be taken into account that high grade cements with specific surfaces in the range of 5000 cm^2/g in many cases can only be produced on ball mills. Thus combi-grinding circuits with HPGRs and ball mills can realize flexible production of a wide range of products with a good efficiency especially for low and medium grade cements.

3.6 Electrical energy demand

Electrical energy comprises between 10 to 15% of the overall energy demand of cement production but is a notable cost driver [HOE, 2013] [MAD, 2011]. Over the last decades the average specific energy demand has decreased worldwide (**Figure 3-7**) [MAD, 2011]. This can be contributed to the on-going optimization and new installation of modern and efficient plant equipment. However, there are counteracting effects: CO_2-emissions can be significantly reduced by the increased use of other constituents than clinker. These in many cases require the cement to be ground finer. GBFS is also more difficult to grind and consequently requires more energy for grinding. Also requirements by the costumers for higher product fineness in some markets and finally growing requirements for exhaust gas cleaning be it for dust abatement or NO_x reduction have contributed to an increase of the specific electrical energy demand [HOE, 2013].

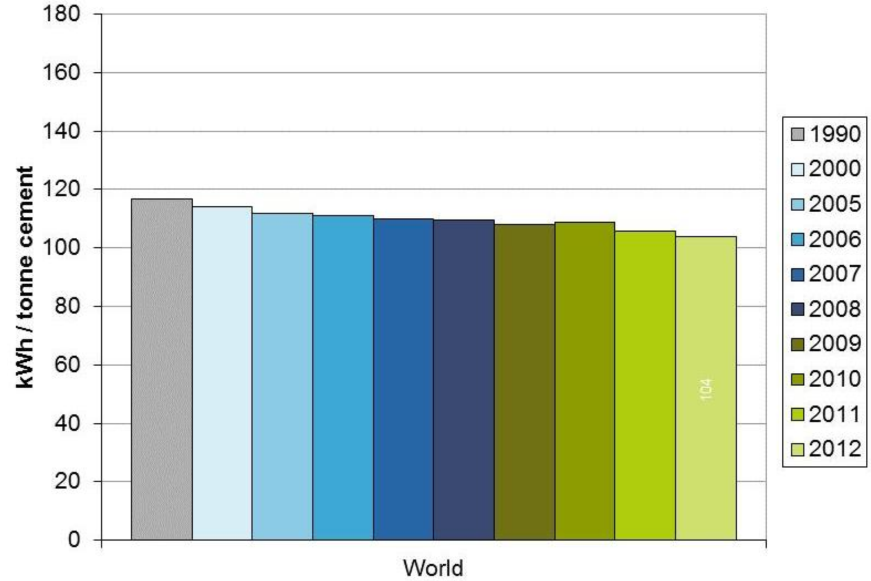


Figure 3-7 Average electric energy demand (All GNR Participants – Word) [GNR, 2015]

An example for market development strongly affecting the specific energy demand is the German market. **Figure 3-8** shows the differences in cement portfolio of the German market between 2000 and 2011. The portion of cements with strength class 32.5 has significantly declined while the portion of higher strength classes has doubled. As already explained above this is connected to an increase in product fineness since early and final strength are both driven by product fineness. Along with the trend towards high grade cements an increase of composite cements can be observed. This development reflects the trend towards CO_2-effcicient products with reduced clinker portions. The number of different cement types increases the complexity of production while hart-to-grind constituents like slag directly impact the specific energy demand.

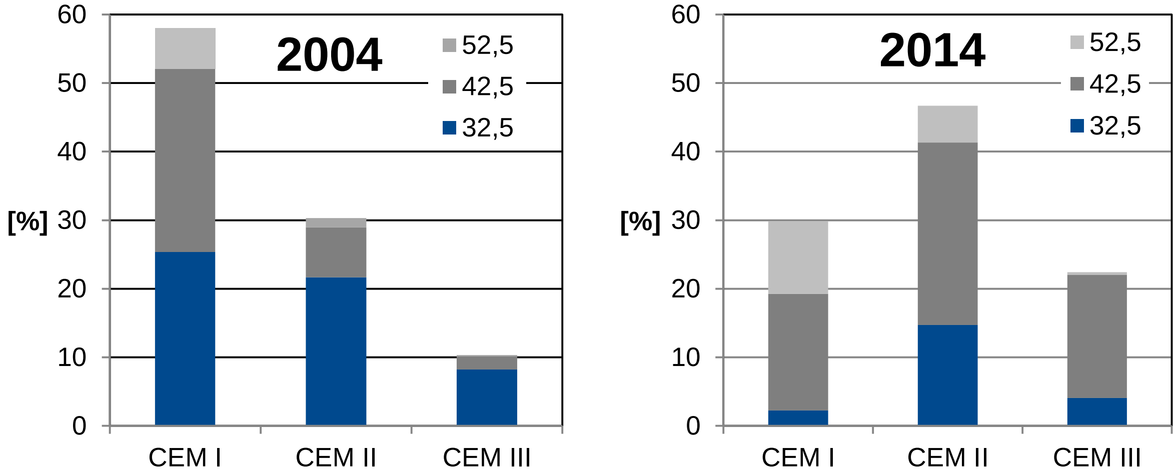


Figure 3-8 Distribution of cement types according to strength classes. [VDZ, 2004] [VDZ, 2014]

For the German market the influence of the product portfolio on electrical energy demand was closely investigated in 2013 [HOE, 2013]. Based on over 660 data sets from actual grinding equipment the energy demand for cement grinding was modelled up to the year 2030. Two scenarios for the development of the cement market were investigated. Scenario 1 was derived from historic development of the cement types over the last decade. An ongoing trend towards higher fineness due to increased portions of higher strength classes and a further reduced clinker-cements ratio are part of this scenario. The second one is based on the assumption that 25% less slag will be available in medium term. This leads to increased use of clinker but also of limestone and fly ash. Regarding the technological development a business-as-usual (BAU) scenario based on today's installed grinding equipment and a best-available-technique (BAT) scenario have been investigated.

Figure 3-9 shows the results of the extrapolation. The increase in fineness will lead to a nearly 10% higher specific energy demand for the BAU case. Due to the high grindability of slag Scenario 2 features slightly lower values. The BAT case utilizes VRMs or combi-grinding circuits and a slight portion of ball mills for parts of the high grade cements. The savings potential of the BAT compared to the equipment installed today amounts to nearly 30%. This is a theoretical scenario that illustrates the overall savings potential by available equipment. The substitution of all installed grinding equipment according to the BAT scenario is not expected due to CAPEX reasons.

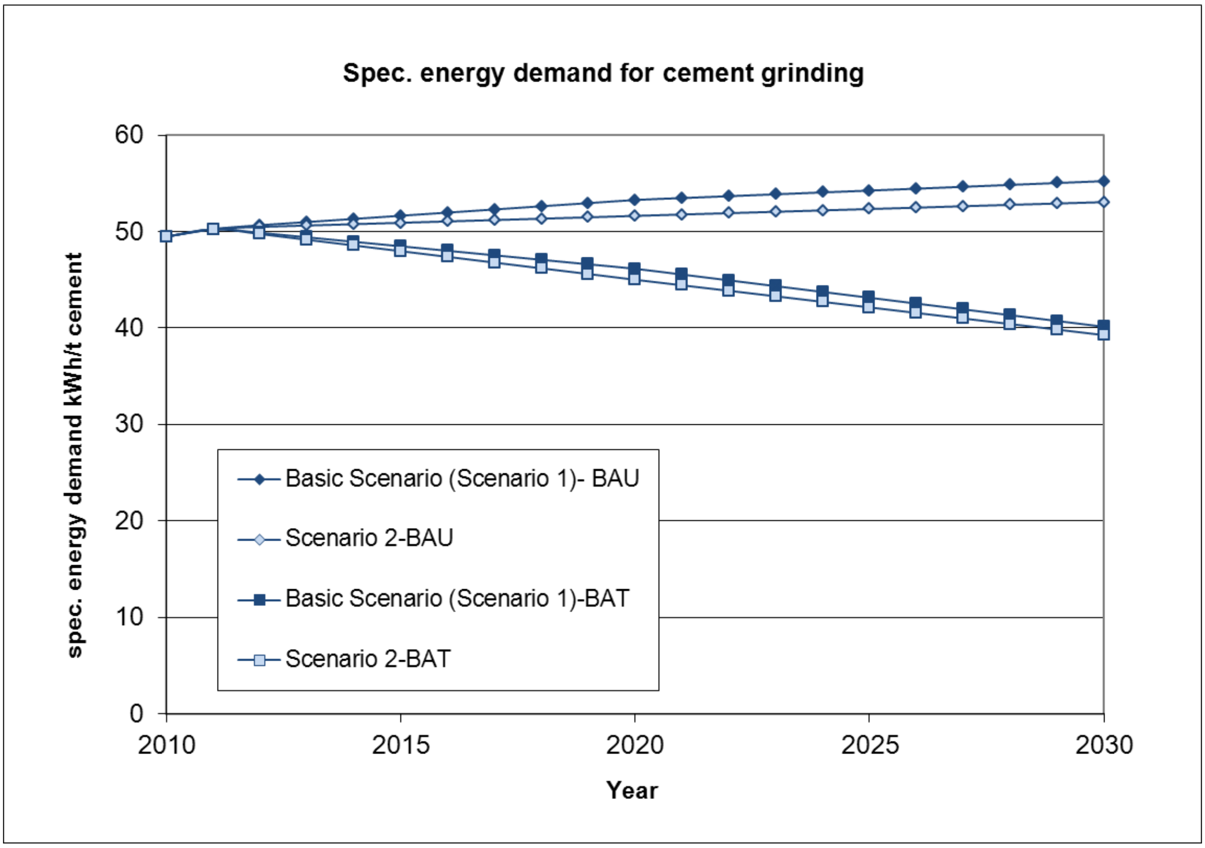


Figure 3-9 Predicted development of the specific energy demand for Scenario 1 and 2 respectively for the BAU and BAT cases.

3.7 Inter-grinding and separate grinding

The aim of many grinding processes is to provide a product with sufficiently high specific surface area to allow efficient reactions during application or in downstream processes. Besides the reactivity of the cement also the particle size distribution plays an important role. The width of the distribution (for example illustrated by the slope of the RRSB distribution) significantly influences the bulk density and thus the water demand and workability of the concrete. The early and final strength of the concrete are to a certain degree influenced by the particle size distribution and the voids between the particles.

During inter-grinding of materials with different grindability the material with lower grindability will accumulate in finer factions of the particle size distribution [MIT, 1996]. Components with low grindability can be over-ground or respectively components with a high grindability under-ground (**Figure 3-10**). It is very difficult to control the PSD when cements with several constituents are inter-ground. **Figure 3-11** shows the differences in grindability of some of the important constituents for cement grinding: clinker, slag and limestone. An increasing share of cements with several constituents requires more and sometimes difficult adaptations of the grinding process when these materials products are inter-ground. This can have a negative impact on the performance of the grinding process or even the final product.

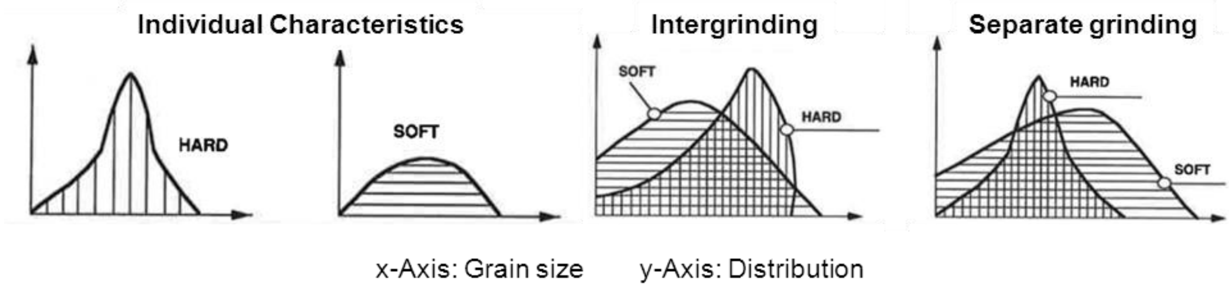


Figure 3-10 Opportunities to adapt the particle size distribution by using separate grinding [MIT, 1996].

These effects can be avoided by separate grinding and blending of cements. Separate grinding allows efficient grinding for each component and provides an additional degree of freedom in designing particle size distribution. Single components can be ground on suitable mill systems at higher efficiencies. The final product is produced by mixing intermediate products. Process technology for separate grinding is well known in general. In most cases existing mill systems can be enhanced by transport, storage and blending facilities. But depending on the given plant layout and the product portfolio the individual technical solutions for separate grinding and blending can significantly differ.

Additional process components such as silos and blending facilities can lead to increased complexity of the whole process. But separate grinding can lead to better control of product quality, lower OPEX and can also increase the flexibility of operation. Intermediate products can be manufactured, stored and used for several products by blending or further comminution. In order to further increase the efficiency of production available constituents, process technology and product design have to be considered all together.

In order to really assess this optimization potential sufficient theoretical models for the variety of equipment in use as well as data on the individual material properties are required. Especially when dealing with complex plant layouts where several intermediate products contribute to the final product the impact of process variations is difficult to determine. Cement clinker as well as the other constituents can feature huge differences in grindability, as **Figure 3-11** shows, but also in granulometry. Clinker properties depend on the chemical composition, burning and cooling conditions while natural materials like limestone can feature huge differences depending on their geological origin.

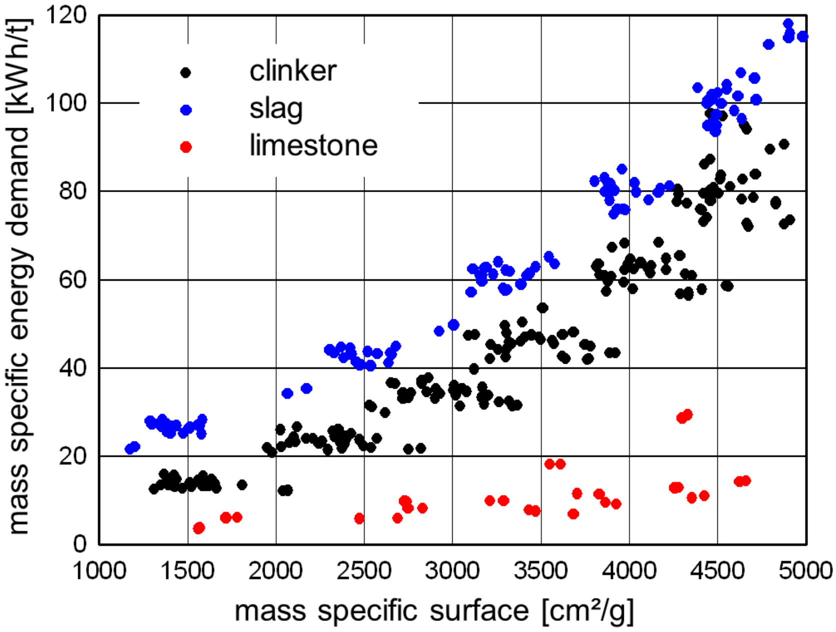


Figure 3-11 Grindability of the most important cement constituents

An overall optimization approach for cement grinding has to take into account the different constituents and their portion in the cements portfolio. Comminution technology and mill capacity can be adapted to the respective materials leading to a variety of theoretically efficient and flexible but also very complex plant layouts. Efficient, reliable and flexible operation therefore requires suitable control technology. A working group has explicitly discussed this topic of plant design during the ECRA Roundtable explained in chapter 5.2.2.

4 Industrial grinding technology

4.1 Efficiency of comminution processes

Today industrial comminution just of minerals makes up about 4% [CEEC, 2015] of the world's electrical energy demand. Next to the cement and lime industry especially the mining industry and the chemical industry as well food processing and power generation require comminution processes. Stress mechanisms, capacities and product properties can vary widely. But the general functions of industrial comminution equipment stay the same. These involve:

- Handling of material: Dosing, transportation to and from the stressing zone including dispersion, classification and optionally drying
- Stressing of material: Provision of energy and transfer of energy to the material including wear protection and process control

Industrial grinding equipment has to fulfil a wide range of requirements defined by product quality as well as by handling and stressing of the material (including the involved sub-processes). Therefore the definition of a technical optimum is difficult. Formulation of a reliable and universal definition for the theoretical efficiency of grinding equipment is already difficult. Thus there are numbers from below 1% up to 19% for the efficiency of a ball mill [FUE, 2002].

As also shown during the ECRA Roundtable event [KWA, 2014] the efficiency of comminution is difficult to define. One approach is the relation of the mills energy demand and the new created surface energy. This results in efficiencies much smaller than 1% that are not meaningful at all. Much more interesting is the specific energy of mill compared to minimum specific energy requirement in so-called 'element tests' or 'mirco tests'. Here at least two possibilities exist:

a. Breakage energy of single particle stressing by compression / by impact
b. Specific energy of an optimized stressing event occuring in the mill (measured in an element test)

The possible definitions a and b have to be discussed based on basic research. During discussions the importance of a clear and universal definition for comminution efficiency was pointed out. Micro tests have shown that efficiency depends on the type of stress as well as the specific work (=stress intensity) of particle stressing. Approach a. therefore represents a more general approach towards the equipment efficiency while approach b. can describe the process efficiency of given comminution equipment. Both approaches have to be investigated closer with regard to a possible application for benchmark purposes.

These definitions both focus only on the actual comminution. Multiple stressing of particles with optimum stress intensity (= specific work just sufficient for particle breakage) leads to the highest energy utilization and consequently to the highest efficiency. But while ideal stressing of material can be realized on laboratory scale industrial scale equipment has to be able to handle large amounts of material and has to cover a wide range of size reduction in a limited space. The requirements given by material handling often restrain the technical realization of ideal material stressing. Thus the efficiency of technical equipment ranges below the theoretical optimum. Dissipation of energy can in theory be represented by an energy transfer coefficient. Simple mechanical dependencies like drive efficiency can be modelled easily by such coefficient. But the handling of large amounts of material especially in dry processes is by far more complex. The explicit integration of material handling on top of the actual comminution into the evaluation of the efficiency of comminution processes shall be investigated during future research activities.

The general scientific definition of efficiency is based on an energy balance. But in industrial practice efficiency often means cost-efficiency and with regard to sustainable production also resource-efficiency. Next to energy there are varieties of cost drivers that contribute to the total cost of grinding. These involve for example wear parts, maintenance costs, grinding aids and expenditures for plant personnel.

Therefore it is essential to understand all functions of grinding equipment. In order to benchmark and compare machinery it has to be divided in sub-processes which can be weighted and rated according to different criteria and individual requirements. Further information on this topic can be found in chapter 5.2.1.

4.2 Comminution in other industries

Comminution is a basic process step required in many industries. In many cases surface area of the processed material is increased in order to initiate or to enhance chemical reactions within downstream processes. In other cases - especially for construction materials - the 3-dimensional properties of the granular matter (meaning particle size distribution and its space filling) are of importance. Increased fineness meaning increased energy expenditure during grinding can lead to higher resource and energy efficiency for the downstream processes. As the intensified use of other constituents for cement products has shown, grinding can significantly enhance resource efficiency but leads to increased energy demand (e.g. for grinding of slag). Thus resource efficient production in industries is strongly connected to efficient grinding technology.

Depending on the capacities, the materials to be ground, the product fineness and additional process specific requirements the technologies used in the various industries can be very different. While during cement production modern raw mills process more than 1000 t/h in pharmaceutics throughputs range around a few kg/h. The size range of interest to the cement industry covers 32 µm – 3 (1) µm while e.g. the chemical industry often grinds to the sub-micron range. Due to its ideal dispersion properties many industries use wet milling, which however is not a suitable choice for hydraulic materials. It is therefore difficult to compare grinding processes among different industries. But as successful examples like the transfer of the HPGRs from cement to the mining industry has shown there is a lot to learn from each other.

During the Roundtable the requirements for comminution in different industries were investigated closely and results are summarized in chapter 5.2.3.

4.3 ECRA database on comminution technology

A literature study on existing grinding equipment in all industries (mainly: mining, coal, paper, chemicals, pharmacy and nutrition) was conducted to get an overview on existing grinding machinery and comminution principles. Grinding performance, general layout, stress mechanisms, state of development, general applicability to cement production and other important information were implemented into the database. The database is an efficient framework for handling and evaluation of information especially with regards to an implementation of general benchmark approach. The current database contains more than 120 grinding devices divided into 8 classes. **Table 4-1** lists some of the major characteristics.

The database includes devices from crushing to finest-grinding of every stage of development, from laboratory scale to industrial scale devices. Different operation modes (dry and wet grinding, open and closed circuit and batch operating modes) and possible abilities for use in the cement industry are also considered. The database is able to connect similar comminution devices with a superordinate device to collect different names for the same device or connect similar devices.

Table 4-1 Categories in the grinding technologies database

Class	Kind of stressing	Development status	Possible use in the cement industry
Chemical / thermal grinding	Impact	Theoretical	Cement grinding
Crusher / coarse grinding	Blow	Prototype	Raw Meal grinding
Cutting	Pressure	Laboratory scale	Granulated blast furnace slag grinding
Jet mills	Friction	Industrial	Grinding of other main constituents
Media mills	Cutting		Coal grinding
Particle bed comminution	Thermal / Heat		Comminution of alternative fuel
Wet grinding	Fluid		Ability for finest-grinding
(Ultra-) Fine grinding	Blending		

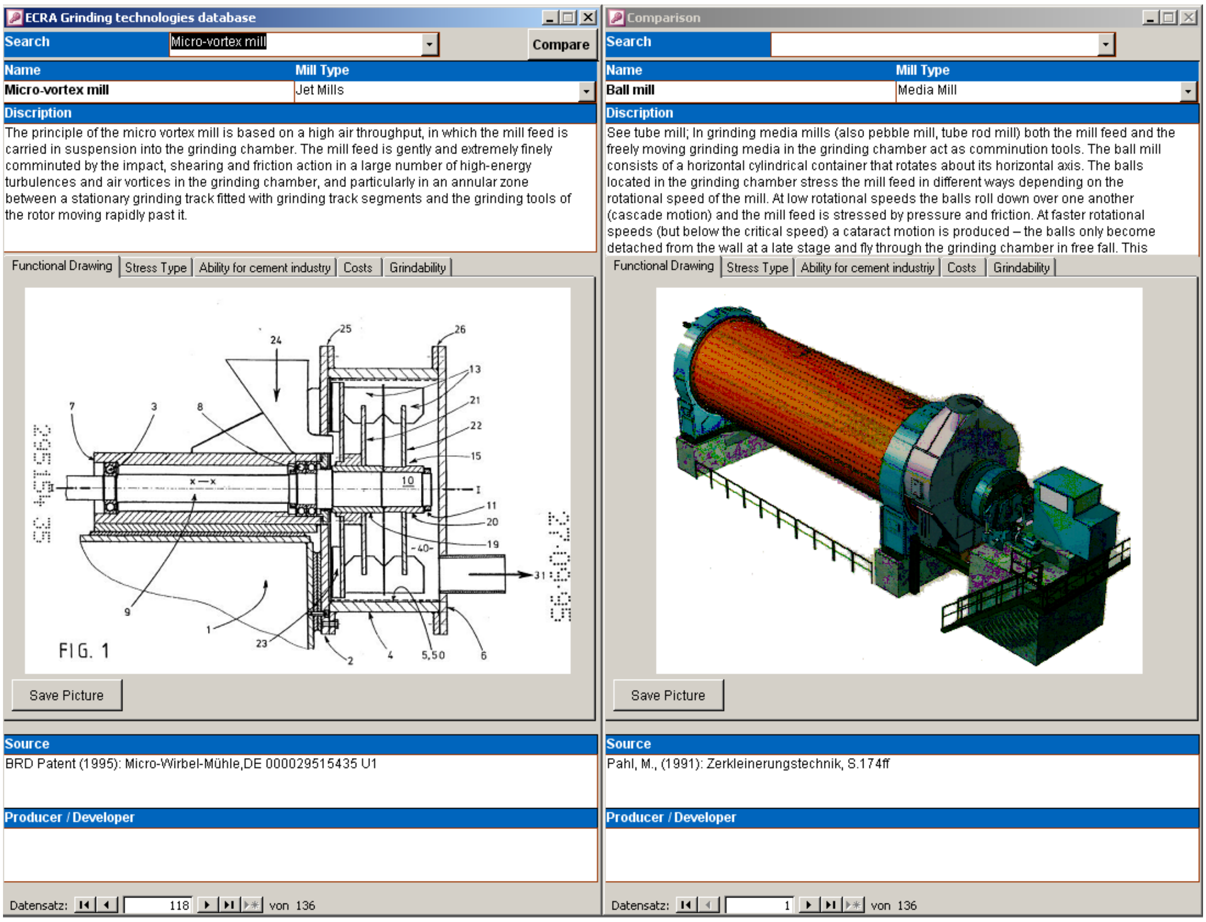


Figure 4-1 Comparison of grinding equipment in the database.

The design of the database considers possible input from future work packages. Additional information can be included very easily and a basic structure for calculation of the „total cost of grinding" is implemented. For an optimal handling "searching" and "comparison" functions have been programmed as well as the possibility for print out.

Similar data-sets e.g. for auxiliary equipment could be included and usage of data for modeling of grinding circuits, up-scaling of experimental devices or benchmarking purposes is possible. Also more complex and individual calculations (e.g. reduction ratio) are possible.

In 2015 an additional update of the existing database on grinding equipment was conducted. Details on the further development of the database are given within Chapter 7.2.1.

The devices mainly used in the cement industry (Ball Mill, VRM, HPGR and Horomill®) are also represented in the database for comparison. The information form the database is exemplary shown for these devices in the following sections.

4.3.1 Ball Mill

Ball mill	(Also known as pebble mill, rod tube mill)		
Mill type	Media mill	Development status	Industrial

In grinding media mills both the mill feed and the freely moving grinding media in the grinding chamber can act as comminution tools. The ball mill consists of a horizontal cylindrical container that rotates about its horizontal axis. Steel balls act as comminution media. The balls in the grinding chamber stress the mill feed in different ways depending on the rotational speed of the mill. At low rotational speeds the balls roll down over one another (cascade motion) and the mill feed is stressed by pressure and friction. At faster rotational speeds (but below the critical speed) a cataract motion is produced – the balls only become detached from the wall at a late stage and fly through the grinding chamber in free fall. The results in impact stressing in addition to the pressure and friction stressing. If the critical speed is exceeded the balls achieve centrifugal motion. This is the least favorable operating mode. Ball mills can have one or more chambers with different charge gradings of the grinding media [STI, 1993]. Length-to-diameter ratio of the mill significantly greater than 1, L/D ~4-6 [PAH, 1991].

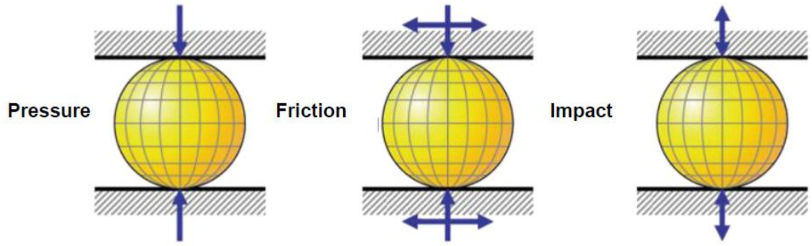
Ability for the cement industry

Cement grinding	☒	Raw material processing	☒
Slag grinding	☒	Additive grinding	☒
Alt. fuel processing	☐	Coal grinding	☒

Operation mode

Open-circuit	☒	Recirculating system	☒
Wet	☒	Dry	☒
Batch process	☒		

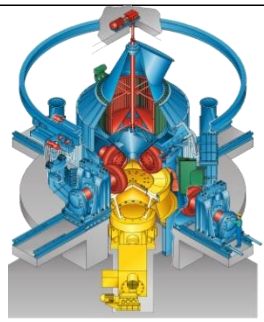
Stress mechanism



4.3.2 Vertical Roller Mill (VRM)

VRM	(Also VRM, vertical mill)		
Mill type	Particle Bed Comminution	Development status	Industrial

Depending on the type, between 2 and 6 grinding rollers roll on a horizontally rotating grinding table, also known as a grinding bowl. The shafts of the rollers are fixed in rocker arms. The grinding rollers are pressed against the rotating grinding table during operation. In small mills the grinding rollers used to be applied using steel springs, but in modern, large mills the rollers are now applied hydro-pneumatically. In the roller mills used today the mill feed is fed centrally onto the grinding table or from the side, in front of a grinding roller. Centrifugal forces carry the mill feed under the rollers where it is comminuted predominantly by pressure and friction. A grinding bed may be formed owing to a rim at the outer edge of the grinding path. Outside the rim there is a louvre air ring for the air flow to carry away the ground material.



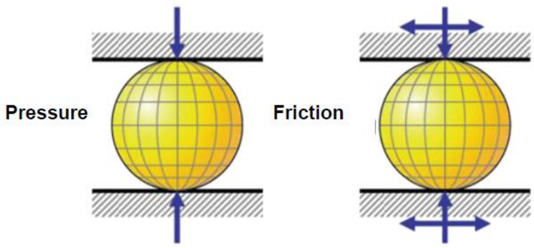
Ability for the cement industry

Cement grinding	☒	Raw material processing	☒
Slag grinding	☒	Additive grinding	☒
Alt. fuel processing	☐	Coal grinding	☒

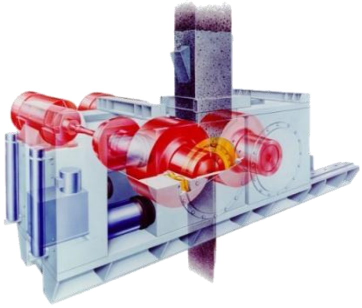
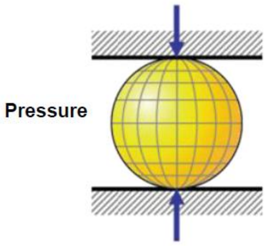
Operation mode

Open-circuit	☒	Recirculating system	☒
Wet	☐	Dry	☒
Batch process	☐		

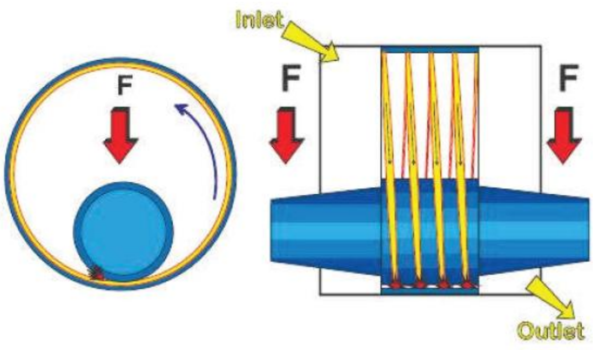
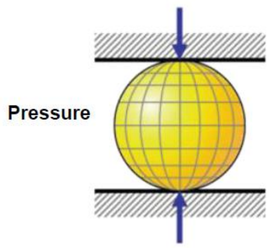
Stress mechanism



4.3.3 High Pressure Grinding Rolls (HPGR)

HPGR	(also roller press)		
Mill type	Particle Bed Comminution	Development status	Industrial
 The feed material is stressed between two counter-rotating rollers with parallel axes. Roller mills can have smooth or roughened (corrugated) roller surfaces. The circumferential speeds of the rollers can be different (pressure and shearing stress, also known as friction) or the same (pure pressure stress). For wear reasons, soft to medium-hard particles are mainly ground by friction with corrugations on the roller surfaces, while very hard material is comminuted with smooth, hardened surfaces and no friction. It is possible to induce single particle stressing, especially with brittle materials, by feeding in particles larger than the gap width, but inter-particle comminution is generally more widespread. [STI, 1993]			
Ability for the cement industry			
Cement grinding	☒	Raw material processing	☒
Slag grinding	☒	Additive grinding	☒
Alt. fuel processing	☐	Coal grinding	☒
Operation mode			
Open-circuit	☒	Recirculating system	☒
Wet	☐	Dry	☒
Batch process	☐		
Stress mechanism			
			

4.3.4 Horizontal roller mill (Horomill®)

Horomill®	(also High-Pressure Grinding Rolls, roller mill)		
Mill type	Particle Bed Comminution	Development status	Industrial
The so-called Horomill® utilizes the centrifugal effect of a cylinder driven above the critical speed in order to transport the mill feed, the ring of material lying against the cylinder wall, via a deflector by free fall into the crescent-shaped grinding gap between the stressing track and pressure-loaded grinding roller. The Horomill has stressing and output characteristics comparable with those of the roller mill. The Horomill operates at grinding pressures that lie between those of vertical roller mills and high-pressure grinding rolls.			
Ability for the cement industry			
Cement grinding	☒	Raw material processing	☒
Slag grinding	☒	Additive grinding	☒
Alt. fuel processing	☐	Coal grinding	☐
Operation mode			
Open-circuit	☒	Recirculating system	☒
Wet	☐	Dry	☒
Batch process	☐		
Stress mechanism			
			

5 Results of the Roundtable event

In order to establish a cross-sectorial research community and to assess the industrial practice of comminution in the process industry a Roundtable event was hold on 4 and 5 November 2014 in Duesseldorf, Germany. About 50 experts from suppliers, universities and research institutes as well as cement manufacturers have participated in the Roundtable event. Also non-cement equipment suppliers and experts from other industries (e.g. lime, gypsum and mining) took part in the event.

The event was structured into two parts:

Part 1: Plenary lectures and discussions (4. November)

Part 2: Workshop-phase with three working groups (5. November)

In order to ensure that all participants had the same level of knowledge lectures on the idea and the possible structure of ECRA's "Future Grinding technology"-project were given along with lectures about the basics of cement production as well as on comminution in general.

The second day started with an introduction to the workshop-phase. Three workshops were conducted simultaneously. The participants were free to join any of the groups. The topics of the workshops were:

1. Machine level:
   "Optimum grinding device, what does it look like?"
2. Plant level:
   "Optimum grinding plant, what is possible?"
3. Industry level:
   "What synergies exist between industrial sectors?"

Figure 5-1 Participants in the ECRA "Future Grinding Technologies" kick-off event

Aim of the workshops was to get maximum benefit from all participants by a creative brainstorming process, collection of ideas, problems and challenges. Furthermore every participant was able to submit his individual notes to ECRA. Every single idea was documented and is considered by this evaluation. All proposals for further work-packages and research issues for the forthcoming phases of ECRAs “Future Grinding Technologies” project are elaborated on the basis of the Roundtable’s results.

A condensed summary of all results including the three working groups can be found in Chapter 5.3. A list of all participants is included in the Annex.

5.1 Lectures and plenary discussion

Besides establishing a network for further research activities, the event provided knowledge on the basic theory of comminution as well as on industrial comminution practice in various industries. The details of the “Future Grinding Technologies”-project were explained by ECRA before an introduction to cement production was given to the experts from different industries.

Arno Kwade, IPAT (Brunswick) gave a basic overview on the theory of comminution and on approaches towards process modelling. He furthermore explained how to define the efficiency of grinding equipment. Size reduction and its efficiency are influenced by the type of stress, the stress intensity and the number of stress events. The grinding equipment capabilities to provide the stress energy to the particles are reflected by an energy-transfer factor. The general importance of process models was pointed out several times during the discussions and in the workshops. Therefore this topic is an integral part of the proposed work packages.

Afterwards short 2-minute impulse lectures were given by various experts **Table 5-1**.

Table 5-1 Lectures and discussions during the Roundtable’s first day

“Cement grinding – Lafarge’s vision” by Didier Dumont – Lafarge, Lyon, France
Summary: - Energy demand does not justify CAPEX (New projects focus on reduction of CAPEX not OPEX) - Describe comminution process, gather fundemental knowledge → apply! - Maintenance has large impact on OPEX – not only energy - New materials (e.g. pozzolana), finer grining (in some markets) - Challenges: Maintenace, dynamic behaiviour of equipment, online productivity tool - Approaches: Classifier is the key to high performance cements, separate / multi-stage grinding, performance management; “process intensification” - New technologies Discussion / Notes: - More specific training (focus: high pressure grinding) - Link fundamentals to practice (→ modeling acc. to Kwade)

“Multi composite cements” by Albrecht Wolter – TU Clausthal, Germany, Germany
Summary: - New “boundary conditions” (resources, energy, concrete formulating) - Complex preconditions for strength (active constitutents, active surface, space filling degree) - Performance of limestone above “dillution” when used in the right size fraction - Separate grinding allows the size adjustment of each constituent (M3K cements) - Clinker is always needed for early strength! Research topics: - Materials + PSD → performance (multi composite cements) - Identifiy appropriate technology for the respective production - Find easily calculable efficiency ratios - Simulations approaches (RASIM, LEE) Discussion / Notes: - Slag availability?
“Current research on particle and fibre comminution” by Mirja Illikainen – University Oulu, Finland
Summary: - Overview on research activities - Comminution of biomass, fly ash, slag - Novel cellulose chemicals for grinding aid / concrete additives (sustainable, for dry and wet) - Wear resistance: geopolymere materials (especially in high intensity impact mills) Discussion / Notes: -
“Current research on crushing” by Erik Hulthén – Chalmers, Gothenburg, Sweden
Summary: - History and research by Chalmers univercity - DEM simulations - Compressive and impact crushing - HPGR

- Replacement of natural gravel (sustainable provision of aggregates) – better shape Discussion / Notes: - Crusher important – higher CAPEX at crusher → lower OPEX at mill - VSI high wear - Chalmers can realize time-dynamic simulation of equipment used in the cement industry
"Do you wish to save energy when grinding clinker?" – Tomas Sverak, University of Brno, Czech Rep.
Summary: - High energy savings by use of (the correct!) grinding aid / additive - Supress reaction of very fine particles by 'passivation' ('too fine particles react too fast') Discussion / Notes: - Mechanical activation required for cement? - "Control surfaces"
"Comminution of gypsum" by Hellie Tsitsiris – Staint-Gobain CREE, Cavaillon, France
Summary: - Comminution needs: From coarse crushing to fine grinding (99% passing 1 µm) - Handling material with broad range of hardness (Mohs 2 to 9) - How fine can we go? Limit of grinding? - What influences breakage probabilities / behaviour? / material parameters / lab scale tests? - How can we tune our processes: Better output PSD, narrow PSD, preweakening techniques, particle shape - Scale up of equipment - Approach: More understanding and less empirism to master our process Discussion / Notes: - "Preweakening" or size reduction of clinker by modification of clinker burning / cooling process (discussed intensivly during the whole Roundtable → workpackage scheduled)

5.2 Workshop-phase

Three workshops were conducted simultaneously. Aim of the workshops was to get maximum benefit from a creative brainstorming process, collecting ideas, problems and challenges. Workshops were conducted from the machine-level (micro) with definition of all its sub-functions up to the more abstract industry-level (macro) to collect synergies between the cement industry and other comminuting industries.

5.2.1 Machine Level: “Optimum grinding device, what does it look like?”

For research and development of future grinding technologies it is necessary to understand grinding equipment and all its sub-processes. Next to stressing of material a variety of “material-handling” tasks is necessary. Therefore a very basic function analysis was carried out by the participants before challenges and approaches for optimization were investigated. Furthermore ideas for the aims of the research project and important challenges to take on were collected (**Table 5-2**).

Table 5-2 Possible goals and challenges to deal with for a research project

<table>
<tr><th>Ideas / challenges / goals</th><th>Remarks</th></tr>
<tr><td>Is there one “ideal mill” for all purposes, materials?</td><td rowspan="2">Definition of “ideal”
→ Multiple criteria to be recognized / universal Key Performance Indicators required</td></tr>
<tr><td>Ideal for What?
- Capacities?
- Target values?
- Properties?</td></tr>
<tr><td>Improve the performance of the comminution at a cement plant by 10-20%</td><td>Related to today’s best available techniques</td></tr>
<tr><td>Optimization of entire devices</td><td>Not only the comminution device itself but also transport, classification, blending, dosing etc.</td></tr>
<tr><td>Principal concepts of “new” milling devices based on basic functions</td><td rowspan="5">Can be realized by a “Benchmarking approach” as initially proposed by ECRA/
Further development of ECRA database</td></tr>
<tr><td>Benchmark equipment</td></tr>
<tr><td>List of criteria to evaluate mill design at the cement industry</td></tr>
<tr><td>Share ideas about grinding technology development</td></tr>
<tr><td>Summary of ideal breakage and classification principles</td></tr>
<tr><td>Mill for very fine cements e.g. 1-2 µm and small amounts? Acceptable energy level?</td><td>Reflects trend towards finer grinding / Sufficient level of fineness has to be chosen with regard to product design and energy demand</td></tr>
<tr><td>Novel comminution device = novel interfaces?</td><td>Interfaces can be regarded as fixed boundary conditions for any development; definition of interfaces is an important input for development at plant-level</td></tr>
<tr><td>Easy operation and maintenance</td><td>Effects on personnel, training and OPEX</td></tr>
<tr><td>Control particle size (distribution)</td><td>Predict effects on particle size distribution a priori (→ modelling required)</td></tr>
<tr><td>Flexible dosing systems
- Location
- “Online”</td><td></td></tr>
</table>

- Material specific	

Table 5-1 Possible goals and challenges to deal with for a research project (continue)

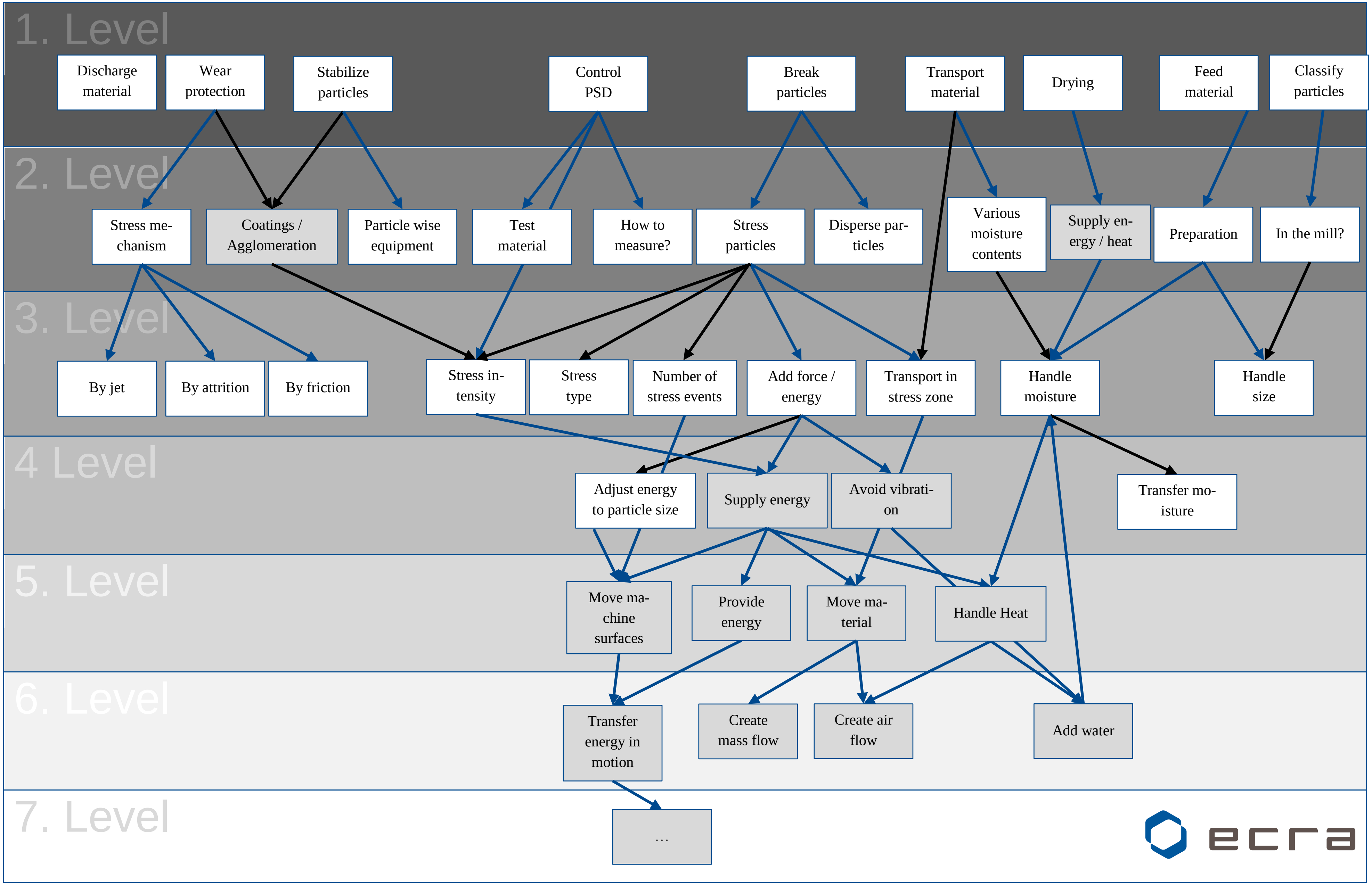
Collected ideas	**Remarks**
Efficient grinding mechanism → besides particle bed comminution	Basics of material stressing (Basic modelling required)
Other mechanisms to transfer energy to particles	
Right energy intensity in our machines? Correct energy transfer to the material?	
Right energy level for particle breakage	
Comminution of particles without “luck”	
Breakage as a function of “energy/time” What are the time scales	
Ball mill optimization Energetically, product quality → Model for mill filling including friction	
Avoid overgrinding (by frequent classifying steps)	
Avoid coatings	See. surface control / grinding aids
Grindability – effects on operation	Test methods? / Control strategies?

By means of a simple function analysis the grinding process was divided into sub-processes and these again were broken down to the very basic functions. **Table 5-3** shows the results of the analysis. The top row (level 1) contains the main functions of a comminution device. The levels below each contain functions by which the functions in the levels above can be realized. Going from top to bottom the question “How can the function be realized?” is answered. Going from bottom to top the question “Why is this function required?” is answered. The graphical representation in **Table 5-3** illustrates the sub-functions of a comminution device. Next to the actual breakage of particles – which is of main interest and features the highest complexity – the interdependencies of the different side-processes can be seen. The points of interest from the plenary discussion are mostly represented within these findings (e.g. wear protection, control of PSD, stressing).

Due to the limited time of the workshop a complete function analysis was not possible. The analysis was therefore only carried out up to the third level. In order to understand the complexity of a comminution device the results were exemplary extended for this report. The main function “Break particles” was stripped down in detail up to the sixth level. While the functions themselves become less complex with increasing level the complexity of interactions grows steadily. All added functions are marked by grey boxes and blue lines

The results were discussed before the background of the question “What does the ideal comminution device look like?”. One of the most important questions throughout the discussion was how the single functions can be rated and compared. In order to fully understand grinding equipment form all industries a universal benchmark approach is required. By understanding sub-processes of comminution equipment, rating their importance and comparing technical solution new grinding equipment can be developed. Current and future industrial challenges have to be taken into account.

Table 5-3 Function analysis of comminution equipment



Based on the functions of comminution equipment different approaches towards optimization were discussed. The main question was:

Where to place the **main focus** for optimization? - On the energy demand or on the product?

This involves:

- PSD (=quality) in front of everything (more important than energy, wear …)?
  - How to predict PSD / quality parameters? / Models?
  - How to measure PSD / quality parameters?
  - What exactly is quality?

Table 5-4 Rating of most important research topics

Collected ideas	Points	Rating
Controllability of mill (e.g. PSD)	10	"Quality " 31,5%
Quality	5	
Product fineness	1	
Chemical behaviour	1	
Flexibility	9	"Flexibility" 29,6%
Flexibility to create different PSD	3	
Properties of feed material	1	
Scale of size reduction	3	
Material handling	-	
Capacity / scalability	-	
Energy demand	9	"Energy" 24,1%
40% less energy than BAT (today)	1	
OPEX (50% to energy)	3 (of 6)	
OPEX (50% to operation)	3 (of 6)	"Operation" 9,3%
Easy to operate	2	
Easy to maintain	-	
Maintenance	-	
Availability / Reliability	-	
Mining: SME / CIM benchmarking standards committee	1	"Contact to mining" 3,7%
Mining: CEEC "Coalition for ECO-efficient comminution" Benchmarking	1	
CAPEX	1	"CAPEX" 1,8%
Environmental safety	-	"Safety"
Operational health and safety	-	

Possible research approaches were collected and peer-reviewed by the participants. Each of them was allowed to attach up to three glue-points to the topics of interest. **Table 5-4** shows the results. From the industry's point of view the control of quality along with the flexibility of production are of highest interest. But these topics are of course strongly linked with energy efficiency.

CAPEX shows only minor relevance during the second day's discussion and rating phase. This was discussed later on and the high relevance that was pointed out during first day's plenary discussion was confirmed. Research activities should focus on reduction of OPEX without high CAPEX. Therefore a stepwise approach focusing on existing plants and equipment is recommended.

The first project step should focus on basics (modeling) and include the use of all available information on comminution before intensive development can take place. Thus a literature study is recommended.

During the final discussion it was pointed out that during all research activities on comminution the "control of (produced) surfaces" shall be considered. Nearly all dry grinding processes are using grinding aid. Therefore this fact should be considered for basic research.

Group 1 - Recommended actions:

- Find ways to change process but also products to reduce energy demand (→ see M3K / Wolter)

- Develop / apply models along with suitable test method to predict particle size distribution (PSD)
    - Literature study (→ What data is required?)
    - Data collection / measurement
    - Modeling (Kwade, Hulthen)
    - Test methods (Faitli, Research Institute)

- Basic understanding of energy losses and ways of stressing, surface effects (e.g. agglomeration)
    - Transfer to existing devices

5.2.2 Plant Level: “What is the optimum layout of a cement grinding plant?”

The second workshop group focused on the design of grinding plants using existing equipment. The aim was to identify the *optimum state-of-the-art grinding plant layout for cement grinding*. During the workshop the following issues were discussed:

- What does “optimum” mean for cement production (today / tomorrow)?
- What has to be optimized in existing grinding plants?
- Flexibility of operation
- Pre-grinding / separate grinding

During discussion it turned out that size reduction is just one task of grinding cementitious material. While indeed size reduction and by that the creation of sufficient high specific surface is important for the hydraulic process, the particle size distribution is of further interest as well as (although today not sufficiently looked at) the mechanical activation of materials with latent-hydraulic or inert properties.

The requirements on ground material are varying depending on necessary product properties. In the cement manufacturing process the particle size distribution is less important for raw material grinding, but of major importance for the final product. However there are distinct different requirements on cement properties depending on environmental conditions (e.g. climate) and application. Joint research on comminution should therefore cover the control of powder properties (like PSD) but not deal with product quality and impact on mortar and concrete properties in detail.

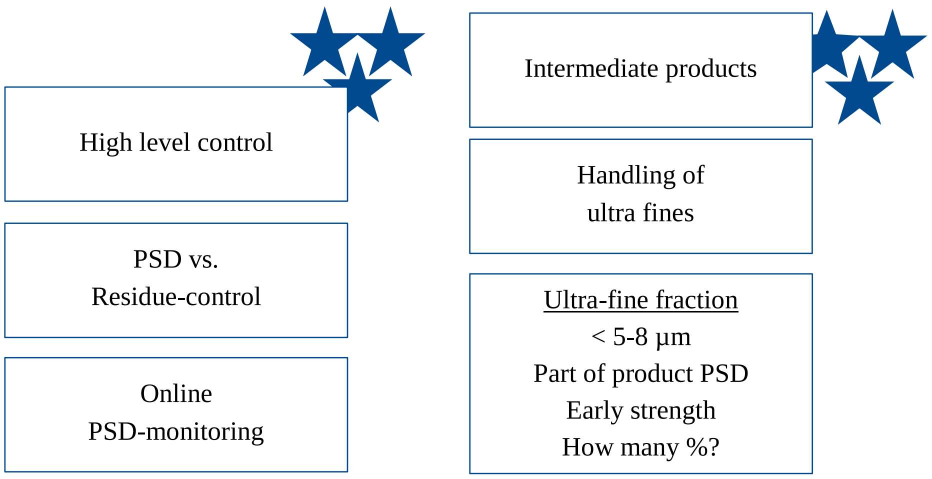


Figure 5-2 Points of discussion rated most important

The points of discussion during the development of an optimum plant design were documented and rated according to their importance. **Figure 5-2** shows the most important points of discussion. Control, also meaning “High level control” of complex production systems and measurement technology (especially for particle size distributions) are of major importance. With regard to flexible and efficient production the intelligent use of intermediate products is essential. Taking into account the advantages of separate- and pre-grinding, also separate grinding according to size fraction is of interest. Furthermore (very) fine grinding can additionally enhance material properties and increase (resource-) efficiency.

A discussion on “fine” and “ultra-fine” grinding can only take place on the basis of an unambiguous terminology. Therefore particles below 5 – 8 µm are regarded as “ultra-fine fraction”.

Strongly connected to the topic on “intermediate products” is general the theme of “flexibility”. Flexibility does not only refer to the product portfolio but depends on multiple requirements including the availability of energy. For flexible production new approaches towards multi-stage grinding are necessary but versatile operation skills are always connected to complex equipment (see **Figure 5-3**). The increasing complexity requires improvement of simulations, models as well as online measurement and control techniques. This underlines the demand for high level control technology shown in **Figure 5-2**. The first step to reach this must be a basic modelling approach. This can be accompanied by the benchmarking process of existing grinding equipment as initially proposed by ECRA. Comprehensive understanding of all available equipment will enable the development of an optimum plant design.

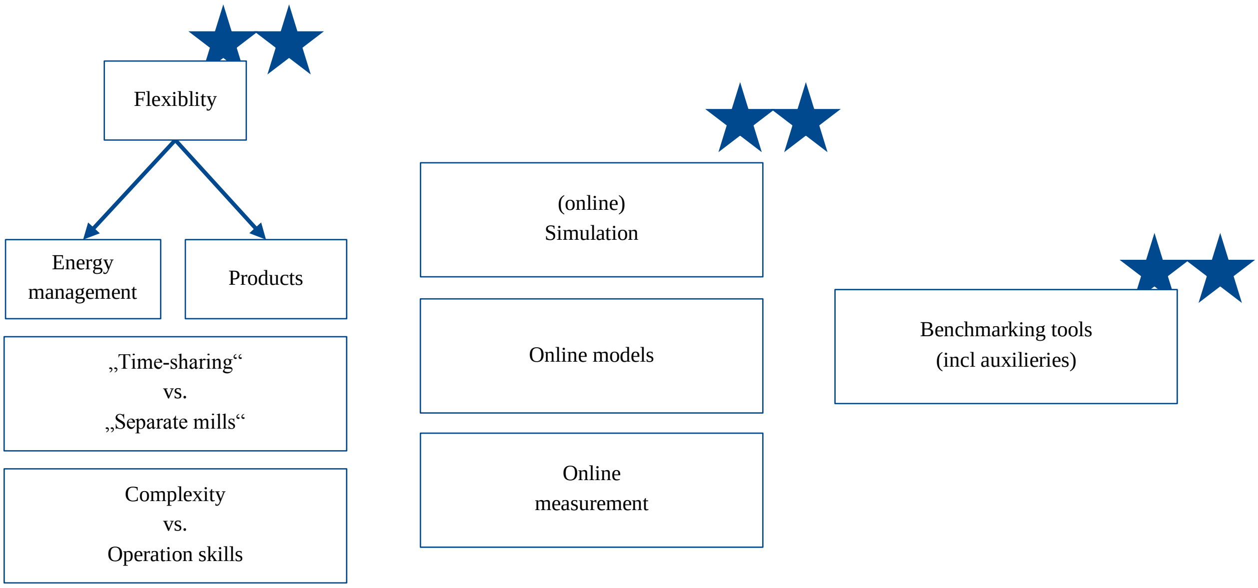


Figure 5-3 Points of discussion rated second priority

Various additional topics which are influencing the major points listed above have been discussed (**Figure 5-4**), for example influences of the overall plant arrangement with regard to heat / air flows but also the interactions with the working environment (OHS) or the clinker constitution.

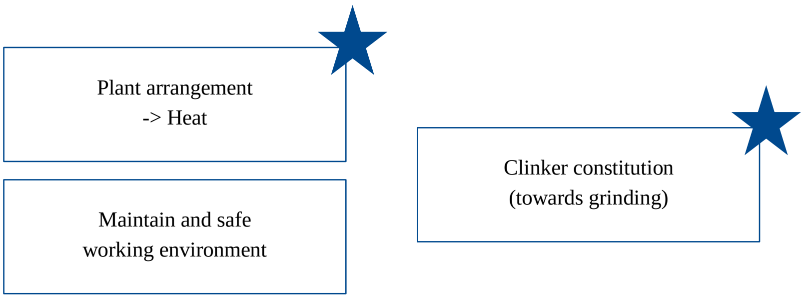


Figure 5-4 Third placed points of discussion in the rating

A lot of savings potential is expected from optimizing thermal energy flows for drying. Using waste heat for drying processes of materials with high amounts of moisture is the most common approach in cement plants. Waste heat recovery for power generation in clinker plants also limits the availability of heat for drying. In stand-alone grinding plants this waste heat sources are usually not available. But depending on surrounding industries waste heat concepts can be evaluated.The better usage of available heat in these plants could simplify the process and reduce total cost of grinding.

The optimization of existing grinding plants (e.g. ball charge grading in ball mills) can improve troughput, efficiency, reliability, wear rates and other important factors. Basic modeling approaches required for benchmarking and long term research activities can directly lead to results of high practical relevance. Decisions on plant design shall only be based on the characteristics of optimized equipment.

Main questions regarding optimization steps are:

- Maintenance / wear behaviour
- Costs: CAPEX / OPEX
- Reliability / performance /
- Clinker replacement (Resource efficiency, CO_2 benefits)
- Energy efficency / - demand
- Control / measurement techniques / automation
- Flexibility

Table 5-5 summarizes all additional points mentioned during the workshop phase. This also includes personal notes and individual discussions. All this information is also recognized and will be part of the general approach proposed by ECRA.

Table 5-5 General points of discussion and further ideas

Chemicals	Main targets	Other "KPIs"	Research proposals
Surface control	Ranking of main targets → done!	Heat demand	Research on 2-cut-/ multi-stage- / Cascade separation
Grind less, use more chemicals	Product / quality	Air "demand"	Connection between cooler and cement mill
Component addition	OPEX	CO_2 emissions	Beta mill
	Maintanance	Water demand	Mobile grinding equipment
	Energy		Less grinding equipment
	CAPEX		Flexibility of silos for storing material
	Energy demand vs. performance		Steeper raw meal grinding
			Fine pre-crushing

The task of the working group was the development of an optimum plant layout. The discussions show that this task is connected to a variety of open questions. Therefore the definitive optimum plant layout could not be developed. But based on the available information at least a proposal for a state-of-the-art plant layout using available technology was compiled (see **Figure 5-5**).

The plant is equipped with a VRM for separate grinding of GBFS. A semi-finish grinding installation with a closed-circuit HPGR followed by a closed-circuit ball mill is available for grinding of clinker, gypsum and limestone. Limestone and clinker are inter-ground in this set-up. Limestone will be over-ground in this scenario but since limestone has to be ground significantly fine than clinker anyway. Separate grinding of limestone would allow better control of the individual PSDs but would also increase complexity. Differences in granulometry of the feed would be critical to a stand-alone ball mill (max. ball diameter) but not to the HPGR. Fly ash is fed to the separator since a large portion of this material already has product fineness. Only the coarse fraction is then fed to the mill. Different intermediate products can be stored and the final cements are produced by blending.

But this layout is still connected to the variety of questions listed above. Therefore it is not yet the “optimum plant layout”. Open questions range from the choice of grinding equipment over the mass flows and intermediate products to the monitoring and control of the process. The optimum technical solution depends on the capabilities of equipment that have yet to be fully understood but also on the individual production situation. It is not expected that cement grinding can be realized by a one-fit-all solution.

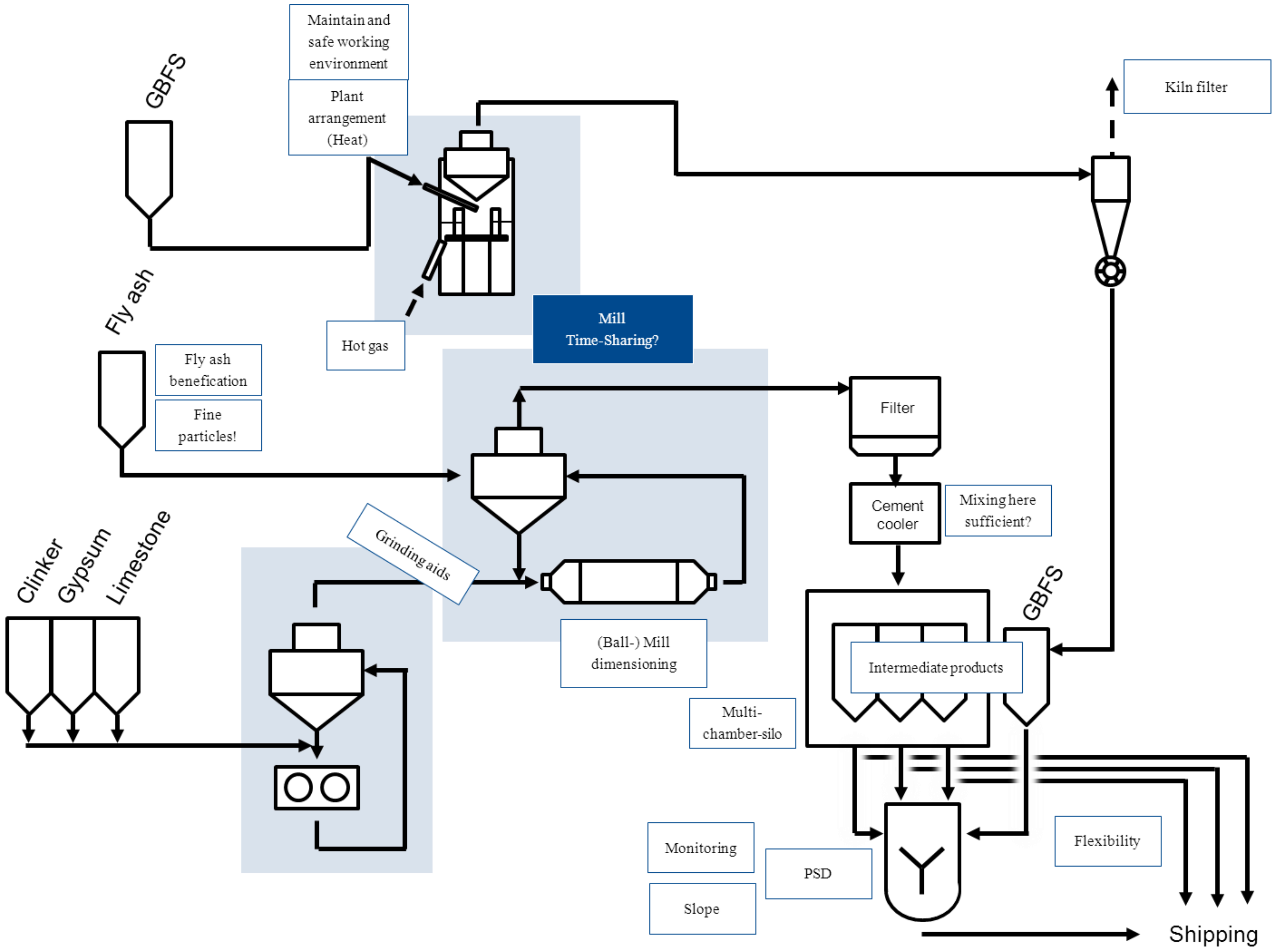


Figure 5-5 Proposal for a plant layout with available grinding equipment.

Group 2 - Recommended actions:

- Develop new measurement and control techniques to improve the control of production by prediction of PSD
- Develop concepts for flexible and efficient production including investigation of product itself
    - Multi-stage grinding and classifying
    - Intermediate products and application-oriented PSD design
    - Online-measurement, -models and -simulations
- Definition of the “ultra-fine fraction” of cement as particles to be below 5-8 µm
    - Responsible for early strength development
- Improvement of flexibility
    - Mill “Time-Sharing”
    - Energy management (→ dynamic energy prices)
    - Product quality
- Plant arrangement
    - Heat sources
    - Transport distances
    - Civil engineering
- Benchmark of existing equipment → allows development of ideal plant design using all available equipment
- Clinker constitution (granulometry & grindability)

5.2.3 Industry level: “What synergies exist between industrial sectors?”

Although materials and fineness can differ widely there are synergies between comminuting industries, even if it is not obvious in every case. The aim in this workshop was to identify the synergies between different industries and collect universal criteria for benchmarking comminution processes as well as common challenges. But also topics next to comminution like powder handling or measurement technologies have been discussed. The agenda for the workshop involved the following steps:

- Identify industries using comminution (of any possible kind)
- Identify synergies, differences and requirements on comminution in different industries
- Comparison (and rating) of requirements
- Identification of promising cross-sectorial research activities

In a first step general approaches towards joint efforts in the field of comminution were gathered. The discussion was dominated by the questions “What information is available to other industries using comminution? / Where are the differences regarding information already available to the industries? / Where can/should combined research take place?”. **Table 5-6** lists the ideas form the first brainstorming.

In addition a systematic approach towards efficient comminution from a very global point of view was discussed – “Focus not only on the mill, but also on the production line itself” – “Why is it always necessary to apply the mill to the process? Why doesn’t the process change according to the needs of the mill?”

Table 5-6 Possible approaches for cross-sectorial cooperation

Learning from each other (Synergies)

- Creative ideas from other industries; how/when is comminution used
    - Expand the scope?
    - Overview on existing research cooperation (Industry, academic, etc.)
    - New ideas to make cement grinding more efficient
- What grinding technologies are used for which types of products?
- Matrix as an overview of comminuting industries
    - Materials
    - Technologies
    - Issues
- Mining industry
    - Simulations / Equipment
- Oil industry
    - Simulations / Flexibility
- Define potential Cross sectorial synergies between industries
    - Define common terminology
    - Cement: fineness acc. to Blaine
    - Mining: fineness acc. to PBO
- Influence of downstream processes on grinding efficiency
- New grinding technology ideas from other industries
- Upscaling small mills to cement plant requirements

Joint research

- Better understanding of the comminution in operation
- Development and use of grinding aids
    - Knowledge about additions for different particles (and solvents)
- Development of new cements on the basis of particles that would agglomerate without chemical additions
- New materials
- Multi stage
    - Grinding
    - Classifying
- How far can simulation take us?

Systematic approach
- Grinding takes place from the quarry to the cement mill   - Pre-treatments before grinding (e.g. crushing) - Increase grinding efficiency - “Why is it always necessary to apply the mill to the process? Why doesn’t the process changes according to the needs of the mill?”
Different added values

- How important is the energy demand per ton/kg/g of the product in different industriesindustries
- What is the more relevent “scope of the project”
    - Decrease kWh/t
    - Decrease demand of energy
    - Redefine the impact in the added value of the product in the society
- Costs CO_2 emissions vs costs of renewable energys

In a second step industries using comminution as important production step were gathered and is was discussed which industries could learn from each other. It was pointed out that there are important differences between processing of organic and inorganic materials. Because of common requirements from the viewpoint of the cement industry construction materials, mining and chemical industry seem to be the most promising partners to learn from and work with. Furthermore it was discussed if suppliers of auxiliary equipment which is directly linked to grinding equipment are a good source for additional advice (e.g. fans / belts for material transport). Based on the importance of sub-processes and auxiliaries for the overall efficiency an integration of these could be a very valuable contribution to the project. The efficiency and reliability of a VRM for example is strongly depending on the air flows in the system. Thus it is influenced by fans, filter system, piping and installed measurement technology.

Table 5-7 shows all relevant industry sectors including the most important sub-sectors. Since some of the terms feature overlapping definitions “Industrial minerals” and “Life science” were excluded from the original list. The terms are still included in the list of sub-sectors.

Table 5-7 Industrial sectors using comminution equipment

Industrial Sector	Sub-sectors
Construction materials	Cement, lime, glass, ceramics, sand, gravel (→ industrial minerals)
Mining	Ores, industrial minerals, raw earths, coal, uranium
Organic materials	Wood, cellulose & paper, biomaterials (→ food processing, → life science)
Food industry	Coffee, cacao & chocolate, cereals, sugar
Oil industry	
Chemical industry	Pigments, inks, plastics, fertilizers
Pharmaceutics	Active agents (→ life science)
Fuel grinding	Solid fuels (coal, petcoke), biomass grinding
Recycling	Metals, concrete, plastics
Suppliers	Fan industry, OEM’s, material engineering

Based on the list of industries the requirements on comminution technology were collected. These involve requirements regarding educts, products and mill operation. In general it was observed that ‘quality’ can have very different meanings when talking about different products. For cross sectorial research activities the introduction of general efficiency- and as far as possible quality-KPIs as well as unambiguous definitions is required. It was observed that the definition of “fine” can cover a very wide range of particle sizes.

In a final step it was tried to link the gathered information on industries and requirements. This should be realized by a rating of the importance for each criterion in each industry sector. But due to the size of the working group and the only small number of different industry sectors represented in the group, the rating was seen as very difficult without additional input. In order to not produce misleading results a general rating of the importance of the requirements was carried out instead. The results were structured and gathered in **Table 5-8**. The rating was carried out by attachment of glue-points.

The rating shows that product properties next to energy demand are – also in other industries – the most important criteria. In general the question was raised if operational requirements are just as important as the demanded product properties. In many cases product properties are given boundary conditions. Process optimization can take place as long as it is not affecting the product. Future activities therefore should include the investigation of how product design can help to increase process efficiency of given technology (→ adopt product to process).

As also noticed in other workshops costs / CAPEX were not mentioned during the discussion. This was discussed explicitly. Since thinking of costs would only hinder the possibilities they shouldn’t be part of the discussion at this early stage.

Table 5-8 Requirements on comminution technology

Operation	Physical properties	Costs	Product-approach	Chemical properties
46%	**39%**	**9%**	**6%**	
Energy (25%) - Power - Waste heat utilization - Efficiency	**Fineness (27%)** - Input / output - Measurement - PSD - Agglomerates	CAPEX	Flexibility	Impact of comminution on chemical properties (mech. activation)
Wear (9%) - Contamination - Abrasion	**Morphology (9%)** - Spec. surface - Particle shape - Physical stability	OPEX	Strength vs. Time	Reactivity
Process control (9%) - Automation - Flexibility - Homogenity - Blending	**Grindability (3%)** - kWh/t - Determination - Hardness	Efficiency	Following concrete evolution requirements	
Mass flow (3%) - Material behavior - Material transport	Crystallinity / amorphous amount		Homogenity of cement quality	
Health and safety	Flow behavior		Leaching of concrete	
Environment - Dust emissions - CO_2 PM 2.5/10	Particle to particle interaction - Pysicaly - Chemical - Electrical - Thermal		Whole process outlook (Cement to concrete)	
Wet / Dry	Concentration		Degree of liberation	
Drying requirements	Primary particles		Raw meal quality	

Group 3 - Recommended actions:

- Evaluate available literature in different sectors and transfer results to other sectors
- Quality is very important – but how is it defined?
  How can efficiency of processes be compared?
- Development of universal KPIs for a benchmark process
- Design database and benchmark tool in a way that 'quality'-parameters can be varied in order to allow application to all industry sectors
- Other sectors as well as suppliers not yet represented in this project should be approached actively

5.3 Summary of the results

Development of new grinding technology is driven by a huge number of different requirements. This process cannot start from a blank page. Therefore ECRA has suggested a cross sectorial benchmarking approach initially with a strong focus on energy efficiency. The aim is to understand existing comminution facilities of all different kinds. Based on the complete understanding of all (sub-) processes new equipment can be designed.

The discussion and the results of the working groups have shown that the control of product properties along with the flexibility of production is as important as energy efficiency. Furthermore the need to reduce OPEX short term without high CAPEX was stressed throughout the discussions. The working groups of the Roundtable event achieved largely intersecting results, despite of its generally independent conduct. Discussions in all working groups led automatically to very common basic points.

Synergies between the cement industry and other comminuting industries exist especially regarding basic knowledge and the understanding of sub-processes. Improvement of knowledge can result in more efficient, stable and inexpensive grinding processes in many industries. Basic process modeling is therefore of interest for all industries.

Improvement of the efficiency of comminution processes requires the holistic view on the entire process. Not only the mill is responsible for the efficiency of the process, also auxiliaries and separation units must be taken into account. Influences between the improvement of the energy efficiency and possible changes to product properties have to be considered. The product properties are of major importance. By customization of the products, production-friendly product design and increased (and well-planed) usage of intermediate products the energy demand of the cement grinding process can decline. But again in order to develop these approaches the basic processes have to be understood and described. The impact of the process on the final PSD has to be determined a priori in order to develop new products and control complex multi-stage grinding installations.

A systematically improvement of the comminution process starts with the benchmarking of existing equipment including all auxiliaries. Cross benefits due to information transfer among different industries are expected. In order to obtain results that can be applied universally developed tools have to be designed flexible. Furthermore universal KPIs for efficiency must be developed while indicators for characterization of product quality must be determined individually in every industry. Regarding basic research and general issues of “powder handling” (e.g. transport) large synergies are expected.

6 New approaches towards industrial comminution

A variety of promising new technologies and interesting approaches towards industrial comminution were discussed during the workshops and among the participants. ECRA has gathered additional information on some of the most important topics with respect to future research activities. These include:

- New grinding technologies
- Examples of grinding technology form other industries used for cement grinding
- Potentials for flexible production
- Improvement of process control

6.1 Stirred media mills for cement production

For the cement industry the ball mill in its traditional design is a tumbling mill using rotating cylindrical grinding chambers to move the grinding media. Due to the relative velocities of the balls the material gets stressed mainly by friction and shear and in comminuted.

Stirred media mills are working with higher grinding media filling degrees. A rotor agitates small balls with (mostly) low velocities in the grinding chamber. Usually these machines are operating in wet mode, because of wear and very high product fineness's (→ agglomeration). Dry operation mode is also possible but not that common. These devices are able to produce very fine materials by high energy densities.

Contacts with water as liquid carrier medium are not suitable for cementitious materials. But for special applications with very fine cements this kind of grinding devices is already used in dry mode. In Sweden for example a stirred media mill is in operation for production of a so called "microcement". Ultra-fine-grinding in stirred media mills is possible in dry operation mode [ALT, 2013].

Cement related research has been conducted using high-speed horizontal attrition mills, which are used for special applications like mechanical alloying and mechanical activation of dry powders. Today the main application of this kind of mill is mostly not just size reduction. High stress energies are able to combine different materials with the objective to create desired material properties by mechanical alloying. Mechanical activation of powders is done by very high energy input into the ground material. Due to energetic imbalances changes of the molecular and atomic structure may occur. Investigations in grinding granulated blast furnace slag (GBFS) have shown increases in compressive strength development of blended cement pastes containing 80 wt.-% slag (**Figure 6-1** right).

In high-speed horizontal attrition mills a high speed rotor accelerates small grinding balls in a static horizontal grinding chamber. Different stress situations occur by contacts between grinding media and the wall, rotor or other grinding media (primary stress situation).

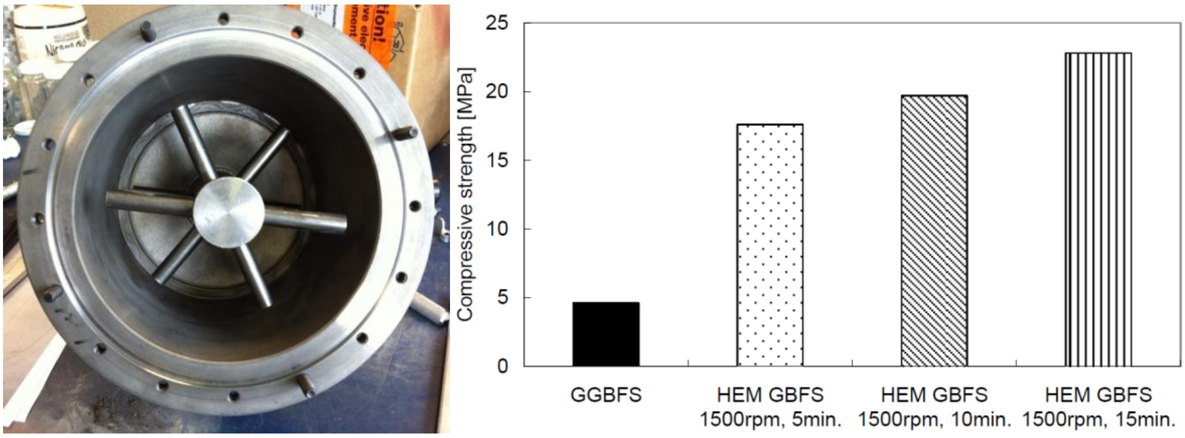


Figure 6-1 Left: Grinding chamber with modified rotor-design. Right: 2 Day-Compressive-strength of cement contains granulated blast furnace slag (GBFS). GBFS fine grinding in a ball mill (GGBFS) or in a high-speed horizontal attrition mill (also High Energy Mill (HEM)) [ZHA, 2009].

Very high operating temperatures in the grinding chamber during operation are measured. Thus different issues (e.g. agglomeration) could be observed. Depending on operation parameters and material properties particle sizes 100% below 10 microns are possible in a dry grinding process. In particular a very short time span to comminute material is necessary. First investigations show that the implementation of a continuous operation mode is possible. But still it is not expected that a device like this can meet the cement industries capacity requirements. Furthermore the energy demand is very high and huge amounts of water are required for cooling.

But this simple device is able to generate very fine fractions of clinker and its other constituents. Therefore it could be used in addition to existing grinding plants to “ultra-fine”-grind a small fraction later on usable for blending special cements. Due to its high operation temperature drying processes and due to the high stress intensity mechanical activation processes (e.g.GBFS) are possible. Current research activities have shown that by optimization of process parameters and mill design the electrical energy demand as well as wear rates can be reduced significantly [TRE, 2015].

6.2 Ecopulser (Krause, Germany)

The *Ecopulser* operation principle is based on supersonic shock waves. The machine is using two contrary rotating disks with shaped bodies (**Figure 6-2**). These bodies are creating colliding shockwaves which are able to comminute material contactless. Particle breakage is not realized by an actual contact to a grinding tool or other particles but touchless by the surrounding media (air flow). Therefore low wear rates can be observed. Material transport is performed without an external fan. The required airflow results from the rotating movement of the shaped bodies fitted to the rotors.

Depending on the material properties the throughput of the *Ecopulser* reaches up to 10 t/h. This kind of device is already in use in the paper industry for wood comminution processes. For wood comminution the reported energy efficiency is relatively high. For comminutions of hard and brittle material like clinker and cement the machine is not yet fully optimized.

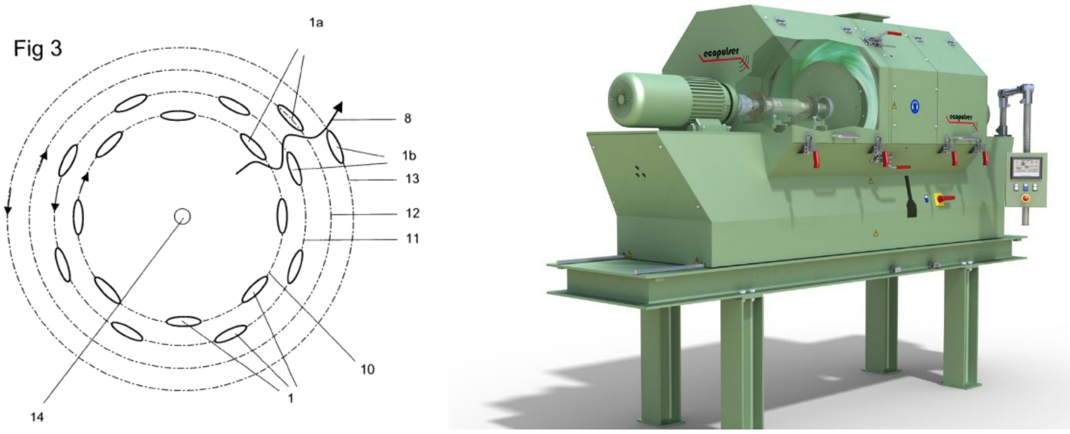
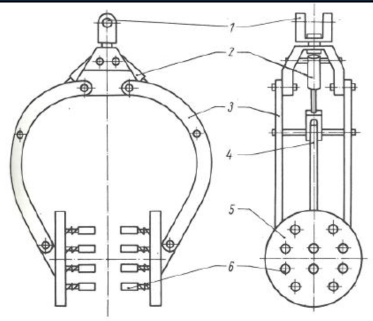
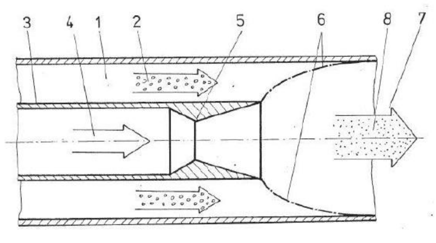


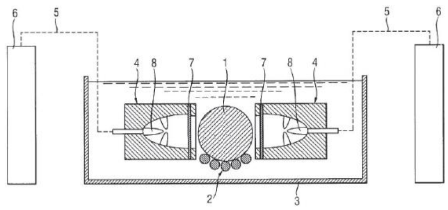
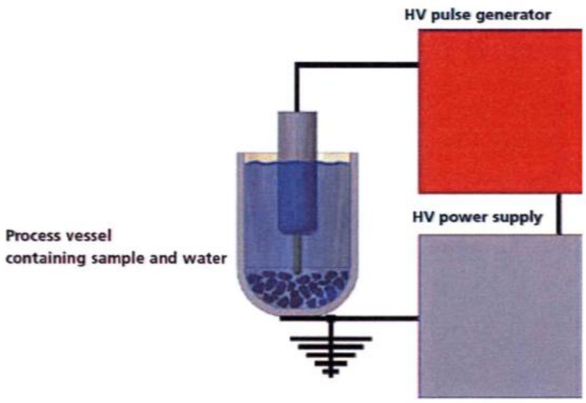
Figure 6-2 Left: Operation principle of the *Ecopulser*, contrary rotating disks with fitted shaped bodies. [KRA, 2009] Right: Overview of the *Ecopulser* [SOM, 2014].

6.3 Non-mechanical / touchless stressing

Comminution in a bed of material today is the “most” efficient industrial-scale dry comminution technique to produce material with cement fineness at sufficient capacities. Comminution is usually done by use of mechanical stress inflicted by contact to surfaces of the machine or in some cases other particles. New technologies like the ‘Ecopulser’ where materials are stressed “touchless” or non-mechanical ones illustrate that comminution is possible in a totally different way. **Table 6-1** shows further examples for such technology.

Table 6-1 Exemplary overview on-mechanical and touchless stressing technologies

Electrothermal crushing
 The electrical energy is directed into the piece of rock to be comminuted either directly through contact electrodes or by magnetic or electrical high-frequency radiators. Closely restricted volumes become heated so that the pieces of rock disintegrate due to the thermal stresses. This is particularly the case when minerals with different specific thermal capacities and expansions are present in the heating channel and the heat builds up in one part of the piece of rock. The advantages of this type of method for direct comminution of large exposed pieces of rock lies in the avoidance of energy losses and the opportunity to use mobile plants without expensive drilling and blasting work. However, the requirements for certain physical properties act against the wider use of this method. [HÖF, 1986]
Gas dynamic crushing
 The invention relates to a method for gas-dynamic comminution of solids, in particular of raw lignite, on the jet principle involving compression waves generated by a compressible working medium accelerated to supersonic velocity (compression shock, shock wave). The purpose of the invention is to use the energy of compression waves of a compressible working medium accelerated to supersonic velocity directly for the comminution and to use the injector or ejector effect of the supersonic flow for conveying the solids. This is achieved in accordance with the invention in that the solids are drawn in by means of the injector or ejector effect by discontinuous action of a pressure difference of the compression waves outside the

working medium flow and are transported from the outside by the compression waves with the subsequent production of a mixture of solids and working medium. [DDR, 1985]
Shock wave grinding
Comminution method, originally for producing ultrafine semiconductor materials. The material to be comminuted (1) is located in the center of a liquid-filled container (3). The material is comminuted by shock waves generated by a diaphragm (7). [USP, 2002] 
SELFRAG: high voltage pulse power technology
Selective fragmentation, or '*selFrag'*, is a comminution method which employs high voltage pulse discharge to promote material's fragmentation, disintegration or disaggregation. The material to be comminuted is together with a process liquid introduced into a process area, in which two electrodes face each other at a certain distance. Between the two electrodes high voltage discharges are generated for fragmenting the material. During the fragmenting process of the material, process liquid is discharged from the process area via radial discharging openings and it is fed  Figure 3: Main components of selFrag-Lab thereafter to a process liquid treatment plant (not shown in the picture), in which the particle load is removed and the electrical conductivity of the process liquid reduced. The reprocessed process liquid returns thereafter into the process area through feeding openings. [SEL, 2006] [USP, 2015]
DevourX: „vortex grinding“ technology
DevourX is a vortex grinding technology, which employs air and sound currents to reduce and break-up solid materials. Material particle size is reduced by a combination of simultaneous physical events caused by pressure, vacuum and sound waves. 

6.4 Grinding aids and chemical agents

Using chemical additives for cement grinding is of increasing importance. Almost every grinding plant uses grinding aids to influence the bulk material properties. Adding these substances to a mill leads directly to changes in the transport and agglomeration behavior which positively affects the material's grindability. But it also affects upstream processes like classification or storage and can even positively influence mortar and concrete properties.. Major part of grinding aids is used for cement grinding but it can also be applied to raw material grinding.

The action of grinding aids is based almost exclusively on the dispersion of the particles being ground. The reduction of strength by the reduction of surface energy (Rehbinder effect) does not have an effect when considering the stress intensity in mills [LOC, 2005]. Most important effect is the reduction of adhesion forces, i.e. van der Waals and electrostatic forces, between the fine particles. This can be only expected from substances which are chemisorbed by the material being ground. It has been shown that some 87% to 98% of the added grinding aids are chemically combined with the cement; only 2% to 13% are emitted with the mill exhaust air [REC, 1986]. Typically propylene glycol, ethylene glycol and triethanolamine or corresponding industrial products are used as grinding aids. Also a growing portion of organic substances is used today.

The altered bulk material properties make themselves apparent as follows:

- Cessation of or considerable reduction in the coating of liner plates and grinding media, particularly in the final half of fine grinding chambers
- Increase in axial transportation speed (improved flowability)
- Changes in movement of the mill feed in the radial plane of a tube ball mill (improved flowability)
- Improved dispersion during air classification; breakdown of agglomerates
- Reduction in agglomerate formation and a shift in the grinding equilibrium toward greater fineness

Dosing failures (e.g. overdosage) can decrease grinding performance. Overconcentration can lead to high flow velocities which means low retention times and therefore a decline in fineness at the mill outlet. Furthermore the grinding chamber can run empty and the majority of the material will be transferred into the circulating load. Too high dosage can also affect packing of cement since the material flow cannot be handled any more.

Water also acts as simple grinding aid [GOE, 1956]. Water injection is used in ball mills for cooling the grinding media and decrease of the coating behavior. The effect is limited since to high amount of water lead to prehydration.

Comminution leads to a creation of new particle surfaces. To control these surfaces is as important as its creation. Especially when grinding products to high fineness it is essential to limit the formation of secondary particles. There the use of chemicals for surfaces control is of great importance for efficient comminution processes. Furthermore the effect of such substances has to be understood up to the final product (e.g. for the cement industry impact on mortar and concrete properties).

6.5 Flexible production

The topic of flexibility was discussed by several working groups. Flexibility on the one hand refers to the product driven by the diversification of the product portfolio and more application-oriented products demanded by the market. But on the other hand flexibility can also refer to the use of equipment and logistics. Mill operation time for example can be restricted by availability or price of electrical energy.

Improvement of the flexibility can be reached by different approaches. One possible approach is the separate grinding by size fraction. Downsized grinding plants with new specialized technology and lower comminution-ratio are able to efficiently produce intermediate products. Fine or finest grinding of a small part of an intermediate product in small specialized facilities can enable the production of products with optimized PSD. Improvement of cement properties by blending of different narrow particle sizes increases the applicability of high efficient grinding units like the HPGR for cement grinding. Blending of narrow particle size distributions of different fineness allows customization of the physical properties of fresh mortar and fresh concrete.

Simultaneously energy efficiency can be increased since the large scale equipment can be operated at lower fineness levels and fewer changes in production are expected. Due to the small capacities CAPEX for these new and more efficient systems is comparably low. An example for multi-stage comminution is the use of additional crushers or pre-grinding equipment before cement mills. By lowering the maximum feed material size and avoiding large differences in the granulometry of the mill feed the ball charge of a downstream ball mill can be optimized and capacity as well as energy efficiency can be increased.

Another promising approach towards flexible production is to organize production around an efficient multi-stage classification system as shown in **Figure 6-3**. Efficient classification means minimum fines in the comminution zone and thus an improvement of the overall efficiency of the grinding process. When handling material with a wide size range (e.g. cement clinker produced by use of alternative fuels) a pre-classification is necessary. Using multi-stage production lines with several grinding- and crushing-units a classification into more than two fractions is required in order to operate all grinding process at their optimum as **Figure 6-3** shows. The different size fraction can be used as intermediate products for blending or can be re-fed to the comminution system.

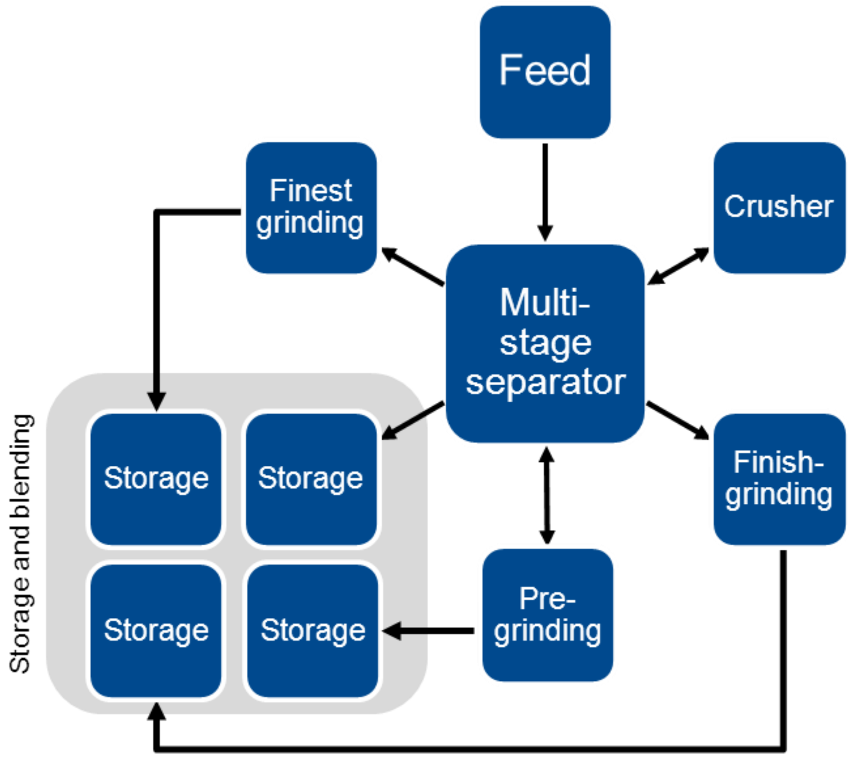


Figure 6-3 Exemplary scheme of a multi stage separator with pre- to post-grinding units

Multi-stage-separators are already in use in other industrial sectors. Also experimental devices have been developed [GRA, 1988]. In general when dealing with multiple materials differences in density have to be considered. Same size particles of different density are separated by the air flow to different fractions.

But also robustness and reliability of grinding plants as well as a “simple process” are essential. Complex processes require skilled personnel for operation and maintenance. Product properties are influenced by a large number of possible impact factors since process variations of all production steps add up for the final product. Therefore a variety of new plants is equipped with large one-mill solutions.

Better measurement and control technology can help to handle increased processes complexity. One key element for this is the characterization of (intermediate-) products by online-systems. Reaction times on production failures can decrease if “real online monitoring” of the particle size distribution and other parameters is available. But it is also essential to understand the controlled variables of comminution processes in order to react on process variation without compromising neither mill stability nor product properties.

Research and development of modern automation techniques for “Smart Factories” can lead to further improvements in operational practice and could increase flexibility without compromising reliability. Production of individual products by same production costs as mass production is possible by using the “Factory 4.0” concept [JAS, 2012]. Using and developing these new techniques can lead to self-optimization, self-configuration, self-diagnoses and cognition of the production unit with the result of increasing process stability, more efficiency and less wear. Basis of this concept is the “Internet of Things”, which replaces central control equipment by “self-controlled” units. Interactions between these embedded systems can control complex grinding plants with a variety of connected units by using modern communication techniques (“Cyber-Physical-System”). Although very abstract these concepts are in small scale tailor made for handling complex multi-stage production and should to be considered for long term research.

7 Proposal for future work packages

For ECRA's "Future grinding technologies" project initially four phases have been proposed. **Figure 7-1** shows the initially proposed time schedule. The Roundtable event, the evaluation and first basic studies are part of Phase I. In this event a huge amount of data was collected and evaluated in order to define the upcoming phases according to the industry's needs. The emphasis of Phase II is on theoretical studies while Phase III can focus on practical small scale activities. Pilot scale research activities are scheduled for Phase IV. Activities as well as the time schedule are proposals. All details will be decided by a Steering Committee in close cooperation with ECRA's Technical Advisory Board (TAB).

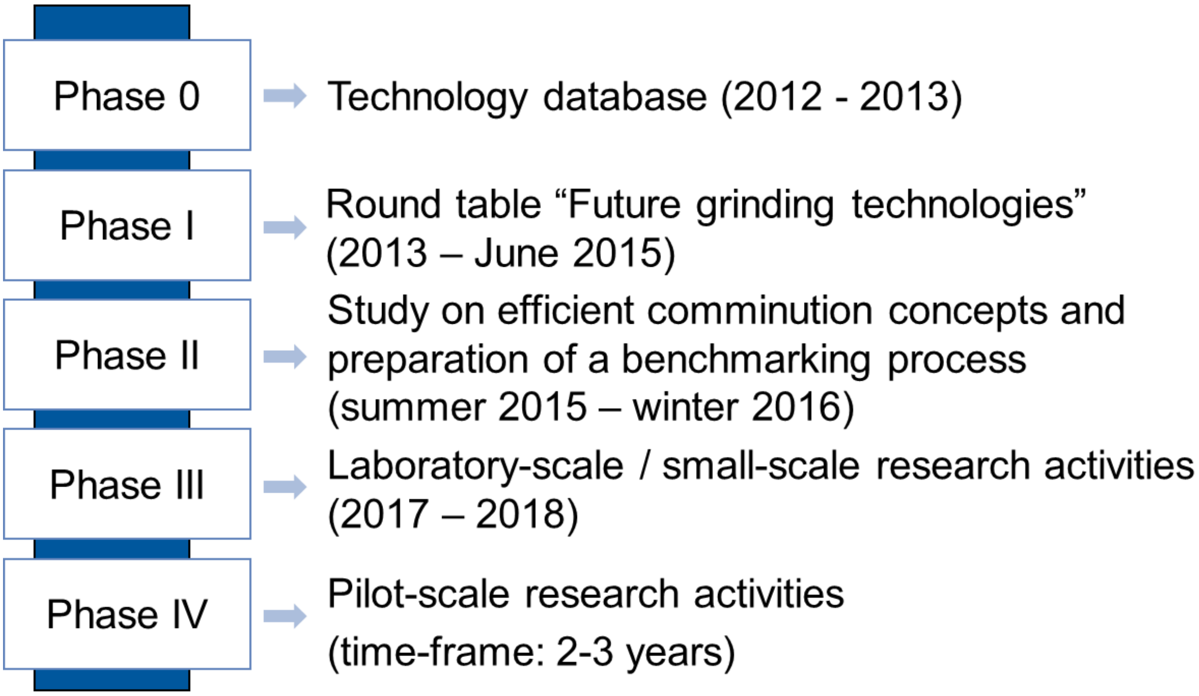


Figure 7-1 Proposal for research phases

7.1 Scientific approach

The initial idea of the project was to initiate a benchmarking process based on a holistic, cross-sectorial documentation of available grinding equipment. In order to realize this, today's and tomorrow's requirements have to be taken into account. Once best practice technologies for each industry sector have been identified, a cross-sectorial development process can be triggered. Besides the actual comminution of material and the classification, all sub-processes such as material handling, dosing, dispersion, wear protection, transport and storage have to be taken into account. The evaluated information will allow the further development of layouts for comminution processes as well as increased usage of alternative raw materials or fuels.

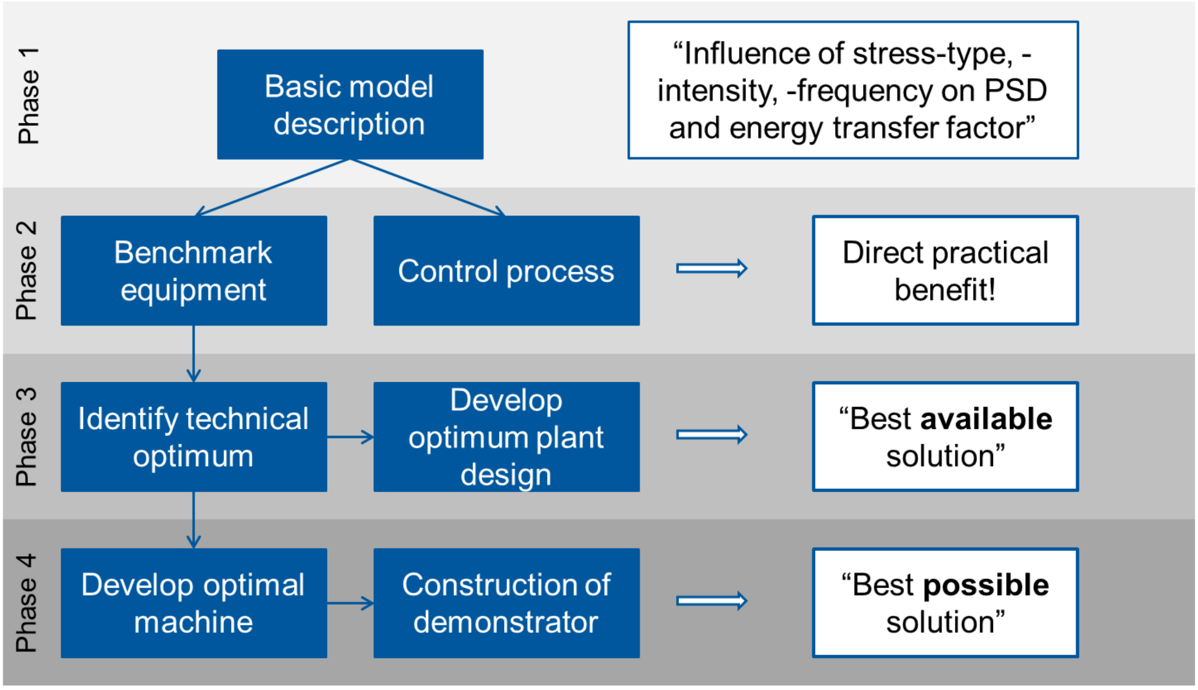


Figure 7-2 Scientific approach for ECRA's "Future Grinding Technologies"-project

Figure 7-2 shows the scientific approach of the project. According to the results of the Roundtable Phase I and II will focus on evaluation of existing literature and application of results to the practical process. It was pointed out that process models are of great importance to the industry. In order to control product quality (mainly PSD) the impact of grinding equipment and process parameters has to be fully understood and predictable. A possible approach was already introduced by Kwade [KWA, 2014] during the plenary lectures. Comminution by different equipment can be described in general by the type of stress, stress intensity and stress frequency. The equipment design can be represented by an energy transfer factor. First basic literature studies on process modelling are already recommended for Phase I.

Based on the first findings these modelling approaches can be further developed in Phase II. On the one hand models can be used to implement a benchmark approach for given technology. Since control of PSD along with flexibility and energy demand are essential criteria for grinding equipment, a general modelling approach is required in order to predict the equipment's impact on the product. In addition findings developed in Phase I and II can be used directly in practice for process control. The reduction of OPEX (without high CAPEX) was mentioned as an important short term goal for many companies. Better process understanding and more reliable prediction of quality parameters will directly lead to practical benefits.

Forthcoming research always builds on the results of the earlier phases and the projects long term aim is of course on the development of future technologies for comminution. But ECRA's "Future Grinding Technology"-project is designed in a way that each phase also leads to results that are directly usable in the industry. Phase III will be built on the developed benchmark approach and focus on the identification of the given technical optimum for comminution. Results will be applied in order to evaluate the "best available solution" for a plant layout with given and available equipment. Furthermore laboratory and semi-technical tests are required for model parameterization and validation.

The aim of the final Phase IV is the development of new comminution technology based on the evaluation of today's available equipment. From the optimal solutions for the sub-processes of grinding equipment the design of a new machine can be deducted. A new device has to feature a significant lower energy demand than today's BAT while all requirements for controllability and flexibility are fully met. At the end of every phase it has to be evaluated if this long-term aim can be realized or not. It is therefore that at the end of each phase the ECRA Technical Advisory Board will evaluate the status of the project and will decide – also based on the budget situation - if and how the project will be continued.

7.2 Proposal for Phase I work packages in 2015

Different approaches for further development of the cement grinding process were collected and the evaluation of the data shows interesting approaches towards this topic (see chapter 5). One of the key-approaches is the use of process models. Since a lot of information is already available a literature study followed by practical application of suitable model approaches was regarded a promising first step. **Table 7-1** shows the work packages for 2015 (accepted by ECRA's Technical Advisory Board in May 2015).

Table 7-1 Phase I work packages 2015

No.	Work package	Type	Status
A2	Evaluation of Roundtable event	Technical study	Finalized
A3	Literature study on modelling	Technical study	In Progress
A4	Clinker size reduction by modification of thermal process	Technical study	In Progress
C1	"Cement & Minerals" session at the ESCC 2015	Coordination / Organization	In Progress

7.2.1 Work package A3 - Literature study on modelling

A variety of process models with different emphasis are already available. For the cement industry an approach for dry fine grinding which can predict the impact on the full PSD is required. Suitable models shall be identified by a literature study and applied exemplary. The grinding technologies database states the basis for the long term benchmarking process in which the models shall be implemented in the forthcoming phases. An update of the database with respect to the outcomes of the Roundtable is also part of this work package.
The work package can be carried out as student work (bachelor- / master-thesis).

Objectives:

- Update existing database on grinding equipment
- Study on basic approaches towards general models for comminution devices (e.g. Stress intensity / stress numberand energy transfer factor)
- Exemplary application of suitable model approach

Deliverables:

- State-of-the-art documentation of available grinding technology
- Documentation of available models of comminution processes
- Application of suitable model approach to comminution of clinker and well known grinding equipment (Ball mill, VRM, HPGR)
- Proposal for general benchmarking approach for grinding equipment

7.2.2 Work package A4 - Thermal process modification

Granulometrie and grindability of clinker influence the performance and efficiency of cement grinding. The effect of lower particle size in the feed material can (acc. to Bond's formula for maximum ball size) be even higher than the impact of grindability. Therefore investigations on clinker size reduction by modification of the burning and cooling process have been discussed and a study was recommended. Alterations of the clinker composition and increasing dust formation in the kiln by modification of the silicate module are possible side effects that have to be taken into account.

The study shall evaluate available literature and summarize possible measures for size reduction by alteration of the burning process. The resulting impact on product as well as thermal and mechanical processing shall be determined. On that basis the reduction potential for OPEX shall be evaluated. The resulting size reduction has to be compared to mechanical processing (e.g. by use of a crusher).

The work package can be carried out as student work (bachelor- / master-thesis).

Objective:

- Evaluate possibilities for production of fine clinker by modification of clinker burning process
- Evaluate impact on grinding performance (handling problems of VRM / HPGR systems)
- Estimation of costs and comparison to use of comminution technology for the same size reduction

Deliverables:

- Description of process modification for production of fine clinker particles
- Impact on cooler operation, dust circuits and chemical product properties
- Impact on grinding performance
- Estimation of costs (CAPEX and OPEX) for process modification and for comparable mechanical size reduction

7.2.3 Work package C1 - ESCC 2015

The European Symposium for Comminution and Classification (ESCC) is one of the world's leading conferences on comminution technology. It will be held in Gothenburg, Sweden from 7 – 10 September 2015. Host is Chalmers University (Prof. Evertsson, Prof. Hulthen)

Website: http://www.escc2015.org

During the Roundtable a dedicated “Cement and minerals”-session featuring topics form all relevant industries was announced. ECRA will support the organisation of the session. Findings of Phase I will be reported at the Symposium.

A short meeting organized by ECRA open to all participants of the Roundtable as a side event to the ESCC is proposed. The aim is to discuss the report, update all participants regarding current work packages and possible funding and initiate the formation of a steering committee and a scientific project committee.

7.3 Proposal for Phase II work packages in 2016 / 2017

According to the scientific approach in Phase II results will be used to further develop the model approach with regard to the benchmark but also for direct practical use. IPAT, Brunswick and Chalmers, Gothenburg (time dynamic modelling for optimization purposes) have a long tradition of research in this field. Next to the theoretical modelling the determination of suitable test methods for material characterization are essential for the parameterization. These can be based on available grindability methods. Current research in this field has been undertaken by University of Miskolc and the Research Institute. All modelling efforts have to be accompanied by suitable validation tests in (semi-) industrial scale equipment in order to ensure applicability.

Dependent on the outcome of the study on the modification of the thermal process (A4) a detailed study on the topic is proposed. Only in case the outcomes are unambiguously positive a second study including on-site plant trials can be carried out.

Table 7-2 Phase II work packages in 2016 / 2017

No.	Work package	Type	Status
D1	Development of model approach for dry grinding equipment (focus: clinker; dependent on outcome of A 2)	Technical study	Proposal
D2	Development of test methods for material characteristics	Technical study	Proposal
D3	Validation tests on grinding equipment	Technical study	Proposal
D4	Detailed study on modification of thermal process (dependent on outcome of A4)	Technical study	Proposal

All work packages are proposals derived from the results of the Roundtable. The work packages can be modified by the steering committee taking into account the outcomes of Phase I.

8 Project organization

In organizing and steering this research project, ECRA will take advantage of its experience from the CCS project. Again, ECRA will set up a Steering Committee that will report to the Technical Advisory Board. The Steering Committee will be constituted with representatives from ECRA members as well as other interested delegates. In any case the Steering Committee shall only be open for representatives from ECRA members and stakeholders who are willing to actively participate or who are willing to take over work packages and/or will contribute to the budget to be agreed on. Also in-kind contributions through work-packages etc. can be seen as a contribution to the budget. The budget required will be set up by ECRA and might also rely on external funding. **Figure 8-1** displays the overall structure.

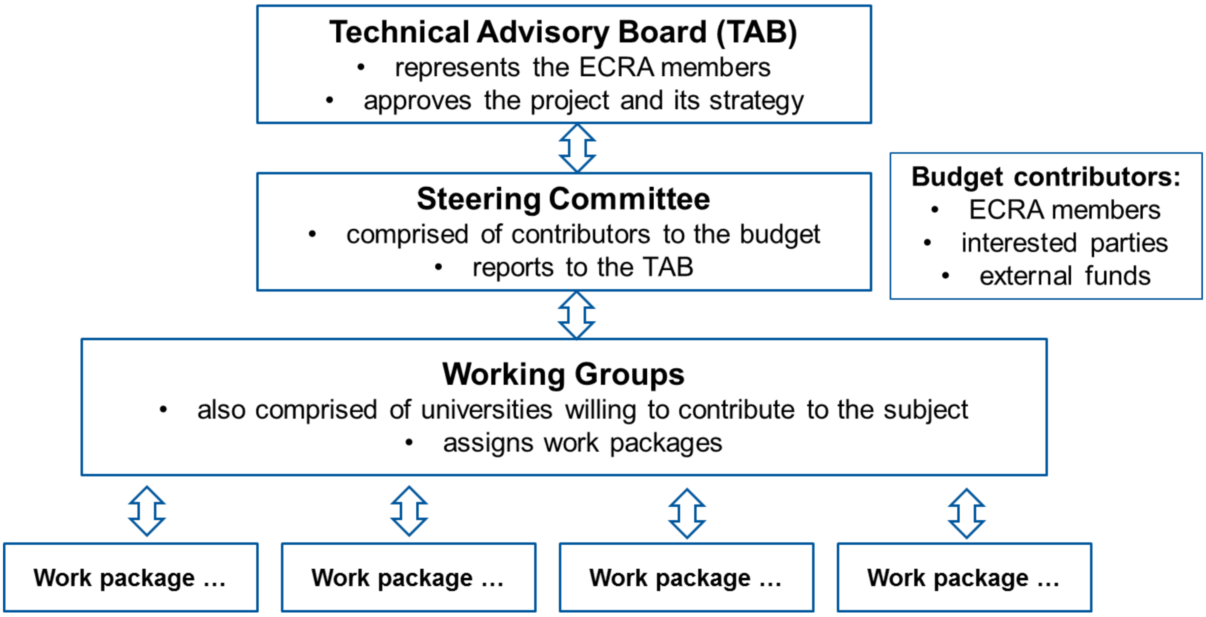


Figure 8-1 Project organization

8.1 Joint working group

During the Roundtable event experts from universities and research institutes have contributed to the subject. In order to ensure the input from experts who are not contributed to the budget the installation of a joint working group is proposed. Work packages can be assigned to parties outside the steering committee who are not contributing to the budget. The research activities are organized in detail by different working groups who report to the Steering committee. It is proposed to install one joint working group in order to allow universities and research organizations access to the project without contribution to the budget. Work packages can be assigned to the members of this joint working group. The joint working group will supervise the research activities of the single working groups, distribute information among all participants and consult the Steering Committee.

8.2 Intellectual property

Keeping in mind that ECRA's interest is to stimulate research activities it is clear that ECRA's main interest is not accumulating intellectual property. ECRA should rather provide the platform for progress, allowing its members to participate in this as much as possible.

In general and unless otherwise negotiated, ECRA's operational principles foresee:

"Whenever ECRA acts as a project partner in external research projects the rules on how to handle intellectual property will be laid down in the project contract, the content of which has to be approved by the Technical Advisory Board. However, all ECRA members are granted for further individual exploitation access to the results and findings to which ECRA achieves access under such contract.

Unless otherwise negotiated, all intellectual property rights arising from research activities conducted by ECRA itself will be owned by ECRA. ECRA members will be granted a world-wide, non-exclusive, royalty-free right to use and take advantage of these intellectual property rights. Consequently all ECRA members are given the opportunity to exploit any result of an ECRA research project that they are interested in. The same applies to external project partners, unless otherwise negotiated. Each ECRA member and every external project partner participating in a research project will keep his intellectual property of his findings and results contributed to the project."

Since at a certain stage of the project on "Future Grinding Technologies" more detailed studies and experimental investigations will be assigned to third parties. It must be clarified how to handle the corresponding intellectual property rights (IPR). The new findings which are expected to be the results of such work packages require a clear understanding of IPR which will have to be implemented into the various contracts that are about to be assigned for the different work packages.

Based on these considerations and on ECRA's experience from previous research activities the following rules for handling IPR were developed. However, the following text represents the current discussion, which might still require this text to be further developed in certain details during the course of the project.

1. ECRA intends at a certain stage of the project to assign work packages for studies and experimental investigations to subcontractors.

2. Any results or rights of these work packages, including know-how, copyright and other intellectual or industrial property rights, obtained in performance of the ECRA project shall be owned solely by ECRA, which shall grant all members of ECRA and the project's Steering Committee the right to use them without geographical or other limitation, except where prior industrial or intellectual property rights exist. In cases where ECRA had to cover costs for obtaining protective rights ECRA must at least be rewarded these costs by the users of these rights. ECRA may also give licenses, publish, assign or transfer them without geographical or other limitation.

3. As the only exemption to this rule, ECRA invites and encourages patents and other registered protective rights to be filed by the subcontractors in their own names on the results obtained in performance of the ECRA project. Should the industrial contractor file patents and other registered protective rights on these findings and results, a system will be established that ensures that all ECRA and the project's Steering Committee members have equal access to such patents and other protective rights by means of a licence on customary terms and conditions granted by the subcontractor. ECRA also reserves the right to bar the subcontractor from licensing a protective

right to entities that are not an ECRA member or a member of the project's Steering Committee.

4. ECRA reserves the right to file patents and other registered protective rights on the results obtained by the subcontractor by industrial contractors in performance of the project, should the subcontractor choose not to file them at all or not in specific countries.

5. Further details shall be part of the individual project contract for each work package.

6. Although ECRA encourages all members to financially contribute to the project, some members may decide not to do so at this time. These members will not be given the possibility to participate in the Steering Committee or the various workshops. They will have the possibility to follow the project only through the results published by ECRA. If ECRA acquires patents or legal rights, these members will be granted access to their use under customary terms and conditions.

8.3 Funding by European PPP / SPIRE

The upcoming phases will deliver short to long term beneficiations to improve the grinding process in the cement industry and related industries. Generally this project is preparing a comminution project in SPIRE (**S**ustainable **P**rocess **I**ndustry through **R**esource and energy **E**fficiency) founded by the European Union. Within Spire's funding up to €15mio for all industries involved, thereof up to €2mio for the cement industry will support the main challenges:

- The urgency to **create growth** and **increase the competitiveness** of Europe in a global market
- The Need to **rejuvenate the European process industry** that is at the basis of the European economy in terms of turnover, employment and generation of technologies for all industrial sectors
- Imperative to **reduce resource and energy inefficiency** and the environmental impact of industrial activities strong industry engagement, large participation, commitment across sectors and boundaries. [SPI, 2015]

„An integrated approach to process innovation is required covering design, simulation, operating conditions and process management together with breakthrough technologies such as grinding.“ [SPIRE Roadmap]

Update: A research topic on “Powder processing” containing the topic of comminution was proposed but was not chosen for the 2015/2016 work program.

Alternative possibilities for European research funding are continuously evaluated and will be reported to all project partners.

European Cement Research Academy GmbH

Dr Philipp Fleiger Kevin Treiber

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10 Annex

Table 10-1 List of participating suppliers, research institutes and manufacturers

Supplier:	Research Institution:	Manufacturer:
Beumer Maschinenfabrik	Brno University of Tech.	BASF SE
Christian Pfeiffer Maschinenfabrik	Cembureau	Buzzi Unicem
Fives FCB	Chalmers University of Tech.	CEMEX
FLSmidth	Portland Cement Association	CIMPOR
Gebr. Pfeiffer	Tech. University of Brunswick	HeidelbergCement
Hosokawa Alpine	Tech. University of Clausthal	Holcim
KHD Humboldt Wedag*	Tech. University of Freiberg	Italcementi CTG
KIMA Echtzeitsysteme	Tech. University of Nuernberg	Lafarge Services Group
Loesche	Turkish Cement Manufactureres Association (TCMA)	Lhoist Western Europe Rheinkalk
Magotteaux International	University of Miskolc	Saint Gobain CREE
Metso Mining and Construction	University of Oulu	SECIL
Netzsch Trockenmahltechnik	VDZ	Südbayer. Portland-Zementwerk
Thyssen Krupp Industrial Solutions		Titian Cement Company
		Vicat

*separate contribution after Roundtable event