ABSTRACT
With the start of the new decade the Mineral Processing chair at Luleå University of Technology has been newly appointed. The scientific redirection of the chair includes several of the important topic areas of advanced mineral processing. From process mineralogy via comminution and concentration processes to mathematical modelling and simulation of particulate processing systems, the mineral processing research at Luleå University of Technology is shaped by the interaction of material, process and equipment. This contribution deals with the positioning of the chair in research and education to meet the upcoming needs in a time where the secured supply with high quality commodities is essential.

1 Introduction
The stimulus for this paper and the alignment with the current and future needs of research and education in the field of mineral processing has been the recent appointment of the author to the Mineral Processing chair at Luleå University of Technology in October 2009, after his predecessor, Professor Eric Forssberg had retired two years ago. At this point, Eric Forssberg shall be again thanked for his long years of activity at Luleå University of Technology, during which he has developed this chair to a nationally and internationally renowned institution in mineral processing.

Even with this change in personnel, and considering newer trends in the field of mineral processing, there will be no radical change in the scientific profile. However, there obviously will be a reorientation and a number of changes in emphasis. This affects both the positioning of the chair in scientific research as well as the establishment of the subject mineral processing in teaching.

Within Luleå University of Technology the Mineral processing chair is part of the Department of Chemical Engineering and Applied Geosciences. This already opens options for interdisciplinary cooperation, both with geology and the chemical technology. And it is now a year ago that a new organizational unit was jointly formed with the Process Metallurgy chair. This further underlines the
integration of the research activities into the metal chain of mining and beneficiation of mineral ores to the final metal products. On the other hand it does not exclude other major fields of mineral processing, such as industrial minerals and aggregates, coal, or the recycling of reusable materials.

The growth in personnel not only relates to the chaired professor. Currently there are two other positions announced in mineral processing to further strengthen senior and junior research. In addition to a new professorship in Geometallurgy with emphasis on iron oxide ores, which will initially be funded by the mining company LKAB, there will be a post-doctoral research assistant with a focus on the application of computational physics to the unit operations in mineral processing.

As a principle the research activities of the chair will continue to be material-related as well as process-related. Being an engineering discipline, the mineral processing subject is characterized by its reference to applications of industrial relevance. Therefore, the chair will still be driven by an applied research, making use of the results obtained from fundamental research. Research will be both experimental and theoretical.

For the experimental investigation of individual processes but also in the consideration of combined processes, the chair’s own laboratory facilities are well equipped with laboratory and bench scale equipment for all unit operations essential to mineral processing (e.g. comminution equipment for different type of stress, various devices for physical separation). Furthermore, there are extensive possibilities for particle analysis and for chemical and mineralogical analysis. Besides their application in research and development the facilities are also used within teaching. Besides laboratory experiments industrial scale investigations are recurrently carried out by on site sampling.

The theoretical research aims at the physics-based description of the unit operations in mineral processing in terms of process models. In addition to a deeper understanding of the process the capabilities of predictive calculation of the process even with changed input variables (material flow parameters, control and design parameters) shall be provided. The model application within a simulation approach allows the analysis of complex processes. The development and application of methodologies for process design and optimization are additional, system-oriented research topics that will be followed up in the future.

The chair is currently integrated in several collaborations and research initiatives. Close cooperation exist with the mining company LKAB, directly and via the Hjalmar Lundbohm Research Center. Other ongoing research and development projects are funded by Vinnova and supported by New Boliden AB. By the Swedish Mine of the Future initiative the Mineral processing chair is also involved in the definition of future national research priorities. Further, a new centre of excellence, the Center for Advanced Mining and Metallurgy (CAMM), is currently established at Luleå University of Technology, in which the chair will participate in the work areas of geometallurgy and particle technology. With regard to cooperation with other universities collaborations already exist or are actually developed inter alia with Berlin University of Technology, University of Leoben, and University of Istanbul. In the field of
teaching also close contacts with the University of Oulu exist in the framework of the Nordic School of Mining.

Opportunities of research funding in mineral processing are in many ways. In addition to the current research funding through the HLRC, the VINNOVA programme and other Swedish third-party donors, it is planned in the future to again participate within the framework of European programmes, as within calls initiated by the European Technology Platform for Sustainable Mineral Resources (ETP SMR) or within the Research Fund for Coal and Steel (RFCS) priorities.

2 Research in the field of mineral processing

Considering the different disciplines within mineral processing a brief overview of selected requirements in research is given in the following. This is to identify the most important technological aspects relevant to the national mining and minerals industry as well as those research and innovation fields, where current and future challenges will lay.

The consideration, without being exhaustive, is based on the relevant specialist literature, feedback from industry contacts and exchange with other scientific institutions and initiatives, such as the Swedish Mine of the Future. The brief analysis of the needs is followed by a description of current and planned activities and developments at the Mineral processing chair.

2.1 Demands in research

The drivers for concrete research needs in mineral processing as well as the consequential topic areas derive not only from the technological change and the development of the world commodity markets. It is also the social needs and the guiding principles from policy that determine the development directions, as related to e.g. environmental and climate protection and sustainability [1], [2]. As a consequence mineral processing research has become more multifaceted and comprehensive.

a) Comminution: Together with the blasting the comminution in crushers and mills stands for 50% of the energy demand in mining. The improvement of energy efficiency and mineral liberation is therefore still an important research topic, beginning with the improvement of individual process steps or comminution devices, via the optimization of single and multi-stage grinding circuits to the integrative mine-to-mill concepts in which the mining extraction is included in the analysis.

b) Process Mineralogy: Despite the growing importance of this cross-discipline with regard to the optimal planning of production quantities and qualities, comprehensive methodologies for particle-based mass and metal balancing as well as their integration in the estimation of mineral and metal recovery within a holistic geometallurgical approach are still lacking.

c) Processing of fine particles: The processing of fine particles gains increasing importance with the mining of poorer and more fine-grained mineral ores.
This is equally true for the growing practice of re-processing tailings from flotation. For fine particles the liberation by comminution and the subsequent separation processes have to be specifically optimized. On the contrary the separation of significantly coarser particles can become necessary when performing energetic optimization of comminution processes.

d) Surface chemistry of minerals: The analysis of the chemical state on the surface of individual mineral particles is an important prerequisite for the analysis of complex composed pulps as well as for the development of new flotation reagents. This continues to be a challenge. Processing of very fine particles smaller than 10 microns here in turn defines special requirements.

e) Gravity separation and magnetic separation: Gravity separation and magnetic separation on the one hand are among the most mature technologies, currently receiving again an increasing research interest due to their relatively low negative environmental impact and lower costs. Here the approaches to process improvement are the integration with other processing options in an overall concept, and an enhanced process analysis using detailed material characterization and process simulation [3]. Also, the dry processing options are momentarily investigated [4].

f) Flotation: Flotation is considered as one of the most important separation processes in mineral processing. In addition to the research requirements on the chemical side (as in water chemistry, mineral-specific and model-based reagents development, separations at low pH values, separation in the fine-scale) it is important to also consider the hydrodynamics in view of larger equipment scales, the necessity to intensify the process or in turn to avoid too high turbulences as in coarse particle flotation.

g) Bioprocessing: The use of microbial metabolic processes, in order to replace several chemical reactions and harmful reagents, has increasingly gained importance in recent times. Besides applications in hydrometallurgy also mineral processes can be modified accordingly [5].

2.2 Aimed research approaches

2.2.1 Process mineralogy and mineral processing

Geometallurgy, as the combination of geology, geostatistics and mineral processing, is one of the fastest growing fields in the mineral sciences. In the newly established CAMM Center for Advanced Mining and Metallurgy the geometallurgy, along with the topic of 4D Geomodelling, will form a work package, led by the Mineral Processing chair.

With the new professorship in Geometallurgy the mineralogical analysis of in particular iron oxide ores will be combined with skills in mineral processing, to optimize both production and product programme in order to meet the expected future changes in the composition of the ores. The overall aim is the generation of integrated models to calculate the expected quantities and qualities along the entire process chain and the development of a comprehensive methodology.
It is envisaged that for this research topic, besides using the mineral processing laboratory facilities, the new high-resolution SEM microscope at the Department of Chemical Engineering and Applied Geosciences will be utilized. The microscope, which has been installed a few weeks ago and is now being put into operation, enables the particularized study of mineral surfaces and grain boundaries. In a next stage of expansion the SEM microscopy and compositional analyses will be combined with image processing and texture analysis to evaluate mineral liberation [6].

In addition to these upcoming developments a research project is already under way, where particle texture analysis is utilized in combination with multi-variate data analysis to develop control strategies for ore grinding circuits.

2.2.2 Research in comminution

Currently an approach for the improvement of energy efficiency within ore comminution is under preparation. Based on the systematic acquisition of microcrack formation and their measurement, starting from blasting via crushing throughout to fine grinding, the basis shall be laid for an improved design and optimization by targeting on the control of this quantity.

Furthermore an ongoing research project on autogenous grinding touches the analysis of contact forces between the mill charge and liners. The objective of this doctoral project is the optimization of mill operation to keep a constant production, thereby reducing also wear. The experimental investigations are carried out using a pilot mill, in which a mill liner has been instrumented to measure the acting forces. The second step is to setup a discrete element method (DEM) based simulation using the obtained experimental data [7].

Systems engineering studies in the analysis of multistage grinding circuits with the aid of modelling and computer-aided simulation [8] will be carried out also in the future. For these purposes several process simulation environments are available at the chair.

2.2.3 Research within separation processes

A major focus of the research work in the field of separation processes is on the experimental and theoretical study of flotation processes. On the one hand this focuses on the improvement of selectivity and recovery, e.g. by the target-oriented development of specific mineral collector reagents [9], the systematic study of the influence of particle size and the optimization of froth formation and destruction. Also the improvement of the system’s hydrodynamic properties through process intensification e.g. by ultrasonic assistance [10] will be an issue in the future. On the other hand, a systems engineering approach with respect to the optimal design of multiple flotation stages is planned in order to obtain information regarding the concentration of certain components within recyclies and the flow of very fine particles.

Only recently a doctoral thesis dealing with the selective coagulation of microorganisms with fine sulfide particles has been recently completed at the chair in the field of biotechnological processing. The results have demonstrated
promising potential for the development of a separation process, so that the continuation of this topic is intended.

As part of the work in the field of magnetic separation a new research project is currently under development concerning the separation in wet low-intensity magnetic separators from the hydrodynamic point of view, after having conducted a promising pre-study. Recently, also a feasibility study on the improvement of a screen separation process within olivine production has been completed, showing that the difficult size separation of this material can be improved by electrically heating the screen plates.

2.2.4 Process analysis, simulation methods and optimization approach

In the field of system analysis for complex mineral processes, the application of modelling and process simulation has been extensively proven [11]. The results from model application, i.e. flow data received from the calculation of material balances, energy-related variables and other dependent variables, are used in the design of new processes as well as in the optimization of existing ones.

In combination with numerical search methods the process simulation can also be applied within optimization calculus. When formulating the optimization problems in mineral processing, usually more than one objective has to be taken into account, frequently with conflicts between production targets, energy and environmental goals. A methodological approach that allows the simultaneous consideration of multiple, even competing targets, is given by the so-called multi-objective optimization [12], which, also known as the concept of Pareto optimization, originates from economics. The application and further development of this approach to mineral processing will be another subject of future research work.

In addition to process simulation and enabled by the development of powerful computing technology, mechanical models based on computational physics have been established in the last years. Starting with the simulation of fluid flows by computational fluid dynamics (CFD) now there are suitable methods available also to describe dispersed solids, e.g. by the discrete element method. While a majority of the research work done so far in this field has been focusing on the bulk solids handling, comminution and partly on agglomeration, the research and development in the application field of separation processes are for most unit operations at the beginning. With the engagement of a research fellow with an emphasis on model development and application of computational physics in the field of mineral processing, this research area will be strengthened in future.

2.2.5 Closing the material cycles and recycling

With regard to the reduction of undesirable outputs, and emissions, but also to increase the product recovery, material cycles have to be closed and material flows to the environment must be treated first [13]. In the field of mineral processing this relates particularly to the treatment of tailings. For the systematic investigation of processing options specific to sulfide minerals a new project proposal has been set on track in cooperation with the geology and hydrometallurgy.
In addition to product recovery the water treatment is a further objective [14]. For example an ongoing doctoral thesis at the chair deals with the process water treatment within molybdenum flotation [15]. Besides the minimization of dissolved components usually very fine particulate matter has to be separated, with the resulting thickened pulps being difficult to handle.

Furthermore the term recycling does not only stand for the production-related recirculation of material flows. Also, the development of technologies for treating industrial and municipal waste will remain, though not as a first priority, a further element of the chair’s research profile [16], [17].

2.3 Staffing and equipment of the chair

The scope of research activities is covered by a team with complementary specializations. Taking into account the current vacancies, the Mineral processing chair comprises the following active employees:

- 4 professors / associate professors
- 1 post-doc research fellow
- 4 doctoral students
- 1 research engineer
- 1 project administrator (partly)

Regarding the number of doctoral students it is targeted to at least doubling it in the intermediate term.

The chair is situated in close vicinity to the other subjects in the Department of Chemical Engineering and Applied Geosciences in the F-building on Luleå campus. In addition to the office rooms a meeting room and a library are available. Laboratories and test facilities include the following experimental equipment:

Bench scale equipment
- Mills (rod and ball mills, attrition mill, wet and dry vibratory mill)
- Hydrocyclone test rig
- Screens (wet and dry tumbler, Mogensen sizer)
- Wet gravity separation (spiral)
- High intensity magnetic separation (Jones separator)

Laboratory scale equipment
- Sample splitting and preparation
- Crushers and mills (jaw crusher, rod and ball mills)
- Wet gravity separation (tables, panner, jig)
- Low-intensity and high-force magnetic separation
- Eddy-current separation
• High-tension electrostatic separation
• Flotation cells (Wemco, Agitair)

The measurement devices for particle analysis include capabilities for the determination of particle size (sieves, cyclosizer, sedimentation, and laser diffraction), particle shape (image analysis, particle density (solid density, bulk density, tapped density), spec. surface area (BET, permeability), surface tension (liquid, powder) and wetting angle, zeta potential (electrophoresis) and turbidity of suspensions. The chemical and mineralogical analyses (by XRF, XRD, SEM) are conducted in the own laboratory and in central laboratory facilities.

The computer environment comprises special software for multi-variate data analysis (SIMCA), for flowsheet simulation (MODSIM, USimPAC and JKSimMet) as well as software for FEM and DEM simulation (EDEM).

3 Teaching in mechanical process technology and mineral processing

3.1 Requirements for the engineering education in mineral processing

Like other engineering sciences the education in mineral processing competes with the non-technical subjects, particularly with the business economics. Thus, it is crucial to design up-to-date study programmes for mineral processing engineers based on modern teaching elements [18], [19]. In addition to the necessary technical content, this concerns:

a) Promotion of analytical thinking: Since the level of special knowledge will become more so in the future, one can not provide every detail in the studies. Instead fundamental knowledge in combination with strong analytical and system technical skills is increasingly important.

b) Promotion of holistic thinking and reflectivity: The increasing complexity of engineering tasks in mineral processing will increasingly require a holistic approach to the whole process chain from geology through mining, processing and metallurgical production to disposal and recycling. This should be accompanied by an adequate understanding for the environment, working conditions and safety.

c) Understanding of business management and economics: As the economy is the main driver in operational practice, it is essential that students soon gain the ability to analyze and evaluate process engineering solutions in terms of productivity and profitability.

d) Project courses as a form of problem-oriented learning: Through the formulation of a problem as a project, i.e. as a unique task to be solved with limited resources in a defined time period by team work, the students are introduced to the subsequent working practices. The opportunity of self organization seems particularly motivating.

e) Practical relevance, experience-based learning: In addition to practical exercises, field trips to operations will promote clarity and understanding.
Theses with industrial background will bring students in contact with potential employers.

f) Internationality: Against the backdrop of a global market for engineering services and products, but also a global labor market in the extractive industries, knowledge in another language and an understanding of cultural differences is an important attribute.

3.2 Courses and other teaching offers of the chair

3.2.1 Basic and advanced courses in undergraduate education

The chair is involved in several study courses within the undergraduate education, in both the first section (bachelor, Swedish civil engineer) and the second section (master programme). This includes:

- Natural resources engineering / Naturresursteknik
- Sustainable process engineering / IndustrIEL miljö- och processteknik
- Mineral and metallurgy engineering
- Exploration and environmental geosciences

Within these programmes the following courses are offered, which are mainly hold in English language:

- Mechanical process technology (contents: particle analysis, particle technology, separation processes) including lectures, analytical exercises and laboratory course
- Mineral processing (ore beneficiation, industrial mineral production, coal preparation, waste treatment) including lectures, analytical exercises and field trips
- Modelling and simulation in mineral processing (different types of crushing and grinding circuits, separation processes) including lectures and computer laboratory classes
- Statistical process data analysis including lectures and computer laboratory classes

In terms of single lectures, the chair further contributes to several interdisciplinary courses. For example within the course in Design for sustainable process engineering the mechanical processing parts within recycling of waste materials are taught.

3.2.2 Post-graduate education

As part of the post-graduate education special courses for the doctoral students are conducted at the LTU. In this context a course on geometallurgy (comprising sample selection, mineralogical and chemical analysis and evaluation, experimentation for the determination of technological parameters such as grindability, separation characteristics, particle-based balancing of the unit operations, predictive production modelling) is planned for the future.
3.2.3 Collaborations in teaching, internationality

For about a year a Nordic cooperation with the University of Oulu in Finland exists in the form of the competence centre Nordic Mining School (NMS). With respect to teaching the objective is to establish a joint master programme and the promotion of student exchanges between the two universities.

In irregular intervals an international exchange of teachers takes place with departments at other universities and research institutions, e.g. with the Berlin University of Technology, or the CSIR in India, in terms of guest lectures and teaching assignments.

4 Summary and conclusions

In summary, the point of departure and the next steps in developing the Mineral Processing chair can be described as follows:

- With the new appointment of the chair and the initiated further human resources development a stable starting position for the further development of the chair given is.
- The prospects for attracting external research funding can be judged positive, also due to the interdisciplinary environment at LTU and the strong industrial environment.
- The direction of the pursued research topics is in line with the current and future requirements for advanced mineral processing research and with the research fields as addressed by the industry.
- Mineral processing education at LTU is in agreement with international curricula in mineral processing. New study courses related to environmental engineering and sustainable resource engineering are well accepted by the students.

5 References


