OPTIMIZATION SYSTEMS DEVELOPED TO IMPROVE THE YIELD ON TUNGSTEN AND TANTALUM EXTRACTION AND REDUCE ASSOCIATED COSTS – THE EU HORIZON 2020 OPTIMORE PROJECT (GRANT NO. 642201)

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Abstract

The main objective of OPTIMORE is to optimize the crushing, milling and separation processing technologies for tungsten and tantalum. Optimization is realized by means of improved fast and flexible fine tuning production process control based on new software models, advanced sensing and deeper understanding of processes to increase yield and increase energy savings. The results explained in this work show this fulfilment with developed or simplified models for crushing, milling, gravity, magnetic and froth flotation separations. A new control system has been developed in this last part of the project, using the developed process models and advanced sensor systems. Validation of models in the simulation environment has been carried out. A pilot plant and real plant validation is planned for the end of the project. Knowledge transfer throughout the project between the Tungsten and Tantalum industry and the project partners has resulted in a strong relation between both which will continue to grow as the project concludes.

Introduction

The modern economy is highly dependent on specific raw materials, and it is envisaged that this dependency will increase in the near future. Most of them are scarce in the European Union (EU) and where they do exist often occur in low-grade deposits, being mixed within complex aggregates, which require processing by means of separation processes which are energy inefficient and highly water consuming as well as requiring high exploitation costs. Tungsten and tantalum ores are two recognized Critical Raw Materials; tungsten production has been lacking in recent years despite its relevance in industry and electronics, among many other fields of application. On the other hand, tantalum is a key element in electronics with clear European external production dependency, as it is naturally scarce in Europe. Table 1 shows the current and near future projects in tantalum and tungsten ores within Europe.

Table 1. List of current and near future projects of tantalum and tungsten exploitations in Europe.

SITE	COMPANY	COMMODITY	LOCATION
Penouta	Strategic Minerals	Ta	Spain
Forecai	Solid Resources	Sn-Ta-Li	Spain
Drakelands	Wolf Minerals	W-Sn	UK
Mittersill	Wolfram Bergbau und Hüutten GmbH	W	Austria
Panasqueira	Almonty Beralt Portugal	W-Sn-Cu	Portugal
Barruecopardo	Ormonde Mining	W	Spain
Los Santos	Almonty Industries	W	Spain
Valtreixal	Siemcalsa-Almonty Industries	W-Sn	Spain
Morille	Plymouth Minerals	W-Sn	Spain
San Finx	Valoriza Minería	W - Sn	Spain
Santa Comba	Galicia Tin and Tungsten	W-Sn	Spain
La Parrilla	W Resources	W-Sn	Spain
Covas	Blackheath Resources-Avrupa Minerals	W	Portugal
Borralha	Blackheath Resources	W	Portugal
Bejanca	Blackheath Resources	W	Portugal
Vale Das Gatas	Blackheath Resources	W	Portugal
Tabuaço	Colt Resources	W	Portugal
Régua	W Resources	W	Portugal
Tarouca	W Resources	W-Sn	Portugal
Oelsnitz	Avrupa Minerals	Au-W-Sn	Germany

To ensure the competitiveness of these projects, the use of energy and water must be optimized and recoveries maximised to reduce the exploitation costs per tonne of product The advanced control of the ore in the processing plants (crushing, milling and separation) is a well suited means to achieve these objectives. Successful control needs the development of new models with higher accuracy than the existing ones and/or expansion of existing models to increase applicability, allowing better adjustment on ore processing. Further to this, the development of advanced sensing techniques such as artificial vision, quantitative mineralogical determination, among other sensing, are necessary to provide appropriate inputs for these models.

To meet this need, the aim of the OptimOre project is to optimize the crushing, milling and separation ore processing technologies for Tungsten and Tantalum mineral processing, by means of improved fast and flexible fine tuning production process control based on new software models, advanced sensing and deeper understanding of physical processes to increase yield and increase energy saving.

Materials

Materials used in experiments were obtained from different European mines and prospects. Samples from these sites were collected from selected areas within the deposit or operating processing plants. Representative sub-samples were then distributed to the OptimOre team laboratories.

Tantalum ore

Tantalum ore was obtained from the Sn, Ta Penouta mine (NW of Spain). It is a granitic ore that was exploited up to de 1980s and it will be open again at the end of 2017. Samples from the open pit and the tailings were used in the experiments. This is a low-grade ore with an average content of 80-100 g/t Ta.

Tungsten ore

Low-grade tungsten ore from the processing plant of the Mittersill Mine, Austria, was used for experiments. These are calc-silicate metamorphic rocks mainly composed of hornblende, biotite, plagioclase and epidote, with scheelite as the W-bearing mineral.

Samples from the processing plant of the Hemerdon mine also were used. This ore has a granitic composition. The main W-bearing minerals in the deposit are in the wolframite solid solution series, with ferberitic species (Fe:Mn>>1) dominating.

Other W-ore used were from Barruecopardo, Morille and La Parrilla, in Spain (Table 1).

Tantalum and tungsten processes

Crushing

The crushing improvements may be interpreted in different ways. The models developed and used in the OptimOre project have been implemented in a process simulator that has the capability to simulate the dynamic behavior in a crushing plant. By doing so the overall model performance compared to real process behavior of the process will increase. This increase in performance can only be evaluated on a case to case basis as referred in previous works on dynamic simulations (Asbjörnsson 2015). It is also important to know that most of the previous crusher models presented in the literature have exclusively been designed for steady state simulations (JKSimMet, PlantDesigner, Bruno, Aggflow and others).

The use of dynamic models and dynamic simulations for coarse comminution will improve the overall performance of the crushing plant (Asbjörnsson 2015). In the present research, crusher models were adapted to work in a dynamic environment. In the specific case presented here, an interlock scenario was presented in "plant saturation" which is the upper limit for the capacity when the physical process is combined with control algorithms. In this case, using steady state simulations, resulted in a plant performance of 1200 tph. When using dynamic simulations, it was shown that the performance could be increased to up to 1470 tph in a best case scenario, which is an improvement of 22.5 % only when looking at one specific situation in the plant, i.e. interlock in the process flow (Figure 1).
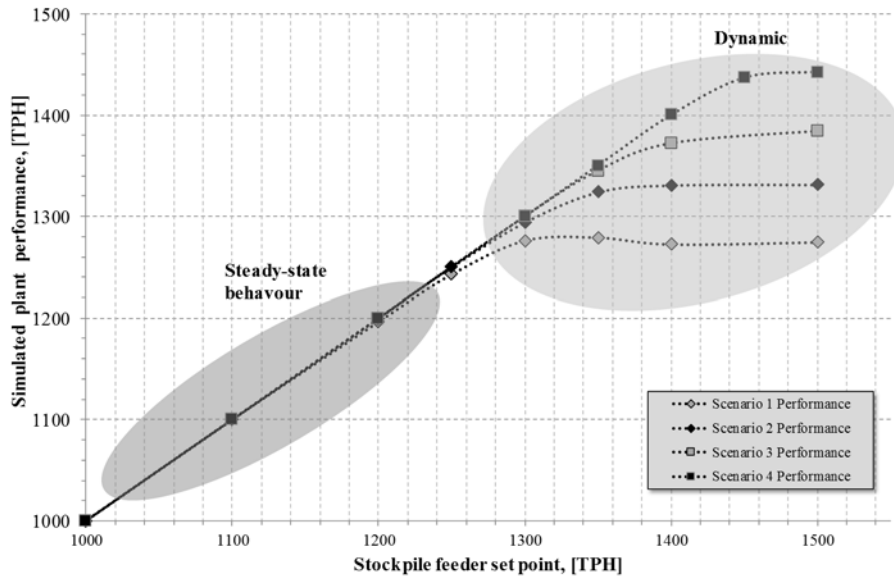
Figure 1. Performance of steady state simulations compared to dynamic simulations.

A concentration model of elements is presented adding a new dimension to crusher modelling that has not been presented previously. The concentration model has been designed to work for all crusher types modelled and the principle modelling structure is shown below.

The concentration model (Figure 2) provides the capability to predict the concentration of the elements in the different particle size fractions after each crushing event.
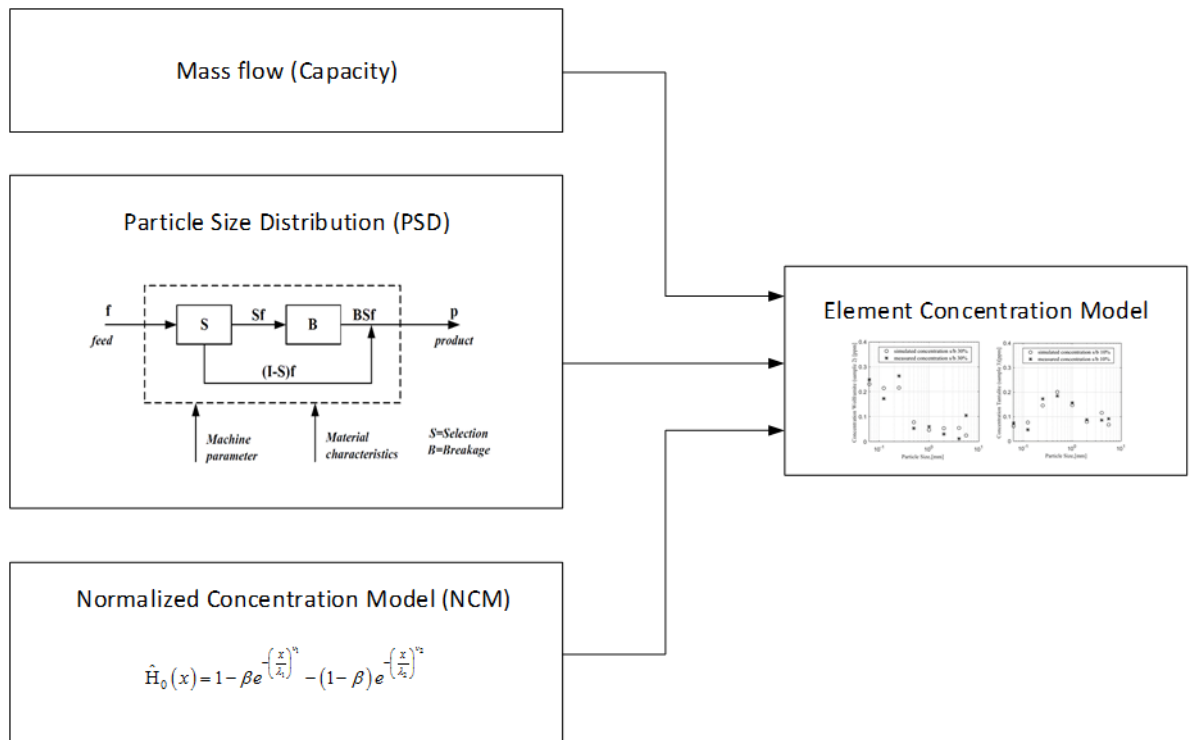
Figure 2. Implementation of the concentration model.

The governing equation for the concentration model is defined as a bimodal Weibull distribution and for the specific application of Tungsten and Tantalum, material parameters has been derived, see table 2 below.

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Table 2. Project materials project for the bimodal Weibull distribution

	ν_1	λ_1	ν_2	λ_2
Mittersill	0.9983	25.256	0.2424	3.172
Barruecopardo	13.775	0.6551	0.1669	23.441
Penouta (1)	12.858	20.102	0.4102	49.978
Penouta (2)	11.768	14.026	0.327	46.544

Grinding

The new grinding models have been developed based on the physical behaviour of the material inside a mill (Figure 3). The capacity for linking the model parameters with the process parameters will allow for their use in the control system in order to save energy and optimize the mineral liberation.
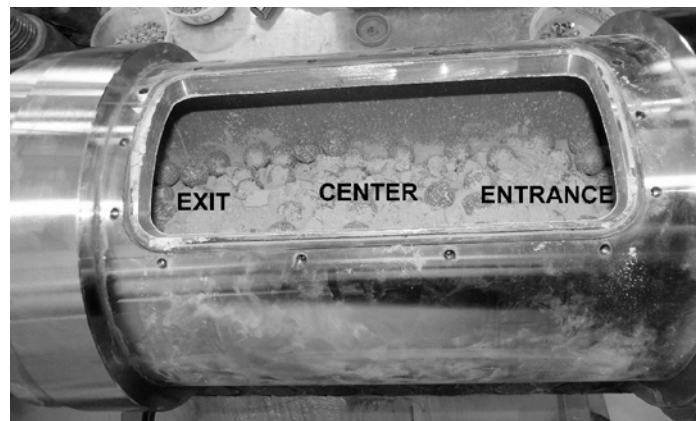
Figure 3. Interior of the mill during one experiment.

The comminution in a continuous dry ball mill can be described as a dual process. However, when a perfect mixed mill process is predominant certain percentage of particles follow a piston flow phenomenon. Observation inside a lab-scale mill, where different samples from the feeding point, the center and the exit of the mill were obtained, evidences this behaviour. The analysis of particle size distribution of the cumulative mass and the differential mass from these samples reinforces this notion.

A mathematical expression is presented as a selection function, which describes the probability of the particles which go to this stage. The exponential regression was based in the plot of the difference between differential mass of the product and the sample obtained from the feeding point of the mill. A new population balance model is presented, with two stages (Figure 4), with a perfect mixed mill solution combined with a piston flow equation as a second stage. The breakage function and the specific rate of breakage function parameters were found using back calculation techniques. Theses parameters were used for validation, showing an excellent prediction of the product.
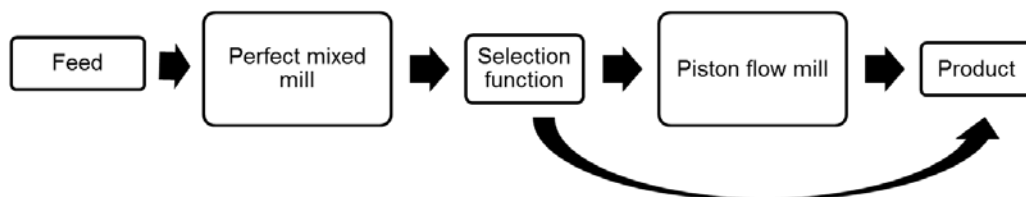

Figure 4. Diagram of the process proposed for a ball mill.

In this final step of the project the work is focused on AG/SAG mills and finishing the linking between process parameters and model parameters. The relation between the energy consumption, the liberation and the size reduction is being studied.

These new predictive models have been tested against established ones and have shown an increase in accuracy well above the objectives set in the project (Figure 5 and 6).
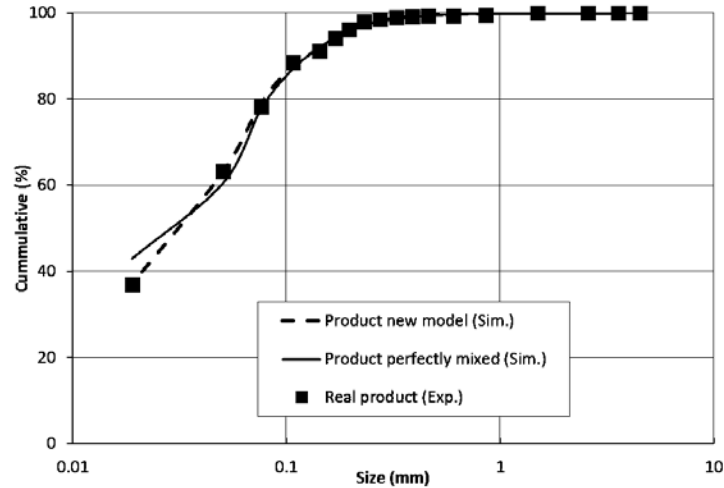

Figure 5. Experimental and predicted curves of the new ball Mill Model (error reduction 69%; Guasch et al. 2017).
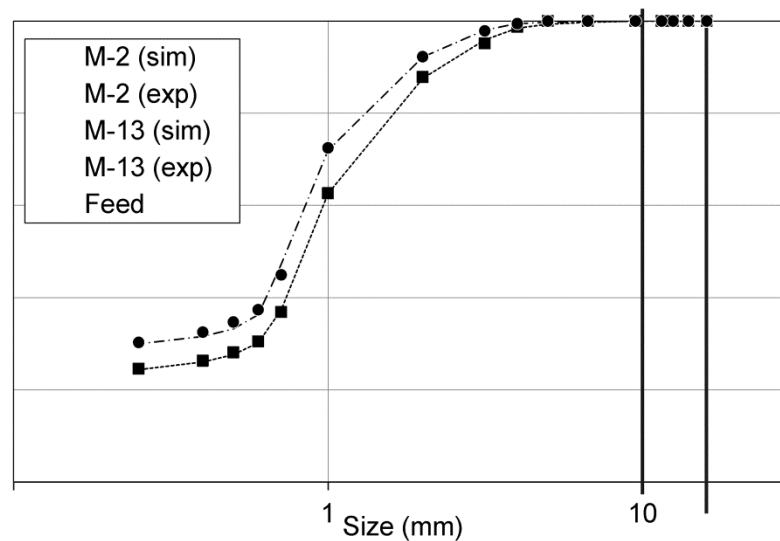
Figure 6. HPGR Mill Model applied in several experiments (M), (data from Guasch et al. 2016).

Error reduction of other models are currently being quantified but are also expected to meet the project objectives.

Gravity separation

The main project objectives in relation to gravity separation were to improve models of gravity separation by implementing quantitative mineralogical data and to use artificial vision to improve the control of gravity separation equipment. Models for gravity separation are not routinely used in processing plants due to the difficulty in obtaining material density distribution as a model input parameter. Quantitative mineralogy offers a means of estimating this value, and is a technology which is becoming quicker and cheaper to operate, with an expectation that systems will be available with quick turnaround (less than 5 hours) within the next 5-10 years. Currently,

a few mines in the world collect quantitative mineralogical data daily (Gottlieb and Dosbaba 2015) and there are systems being designed to further speed up processing (Dosbaba and Gottlieb 2015). The use of quantitative mineralogy to allow for routine modelling of gravity circuits has been investigated. Processing plants rely on human monitoring to react to changes in material and plant conditions. The large interplay of process units makes this difficult to optimize. An artificial vision system would be invaluable as it would allow for the monitoring of multiple units and real-time reaction to changes in plant conditions.

Modelling work focussed on developing methods to integrate quantitative mineralogical data into gravity separation models. Many of these models partition the feed into size and density categories and predict the relative recovery of each category. The accurate translation of mineralogical data into these categories and the accurate prediction of individual particle recovery (Figure 7) is an important and non-trivial task. The novel approach developed to achieve this is divided into two parts: in 'Model Part A' a model of the unit operation predicts recovery of size/density categories and in 'Model Part B' the mineralogical data is integrated with the inputs and outputs of 'model Part A'.
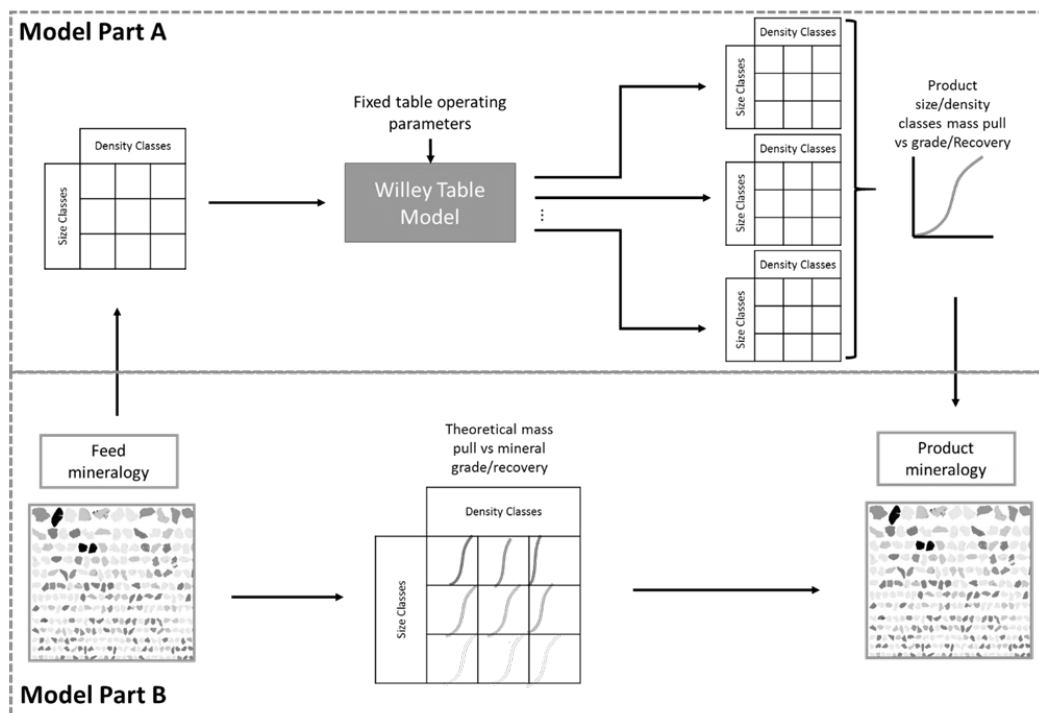

Figure 7. Quantitative mineralogical modelling approach for gravity separation

Quantitative mineralogical data was obtained using a FEI QEMSCAN 4300 with Zeiss EVO 50 SEM. Modelling was based on individual particle data extracted from false colour images using a Matlab code. Model Part B was used to predict the mineralogy of products of a spiral concentrator using data obtained from the Drakelands processing plant (Figure 8). There was good agreement between the predicted and measured mineralogy. Some of the observed error in the data is a result of recovery estimation using the n-product formula, sample representivity is also an issue. Work is currently being undertaken to reduce this error by matching mineralogical data to bulk chemical analysis.
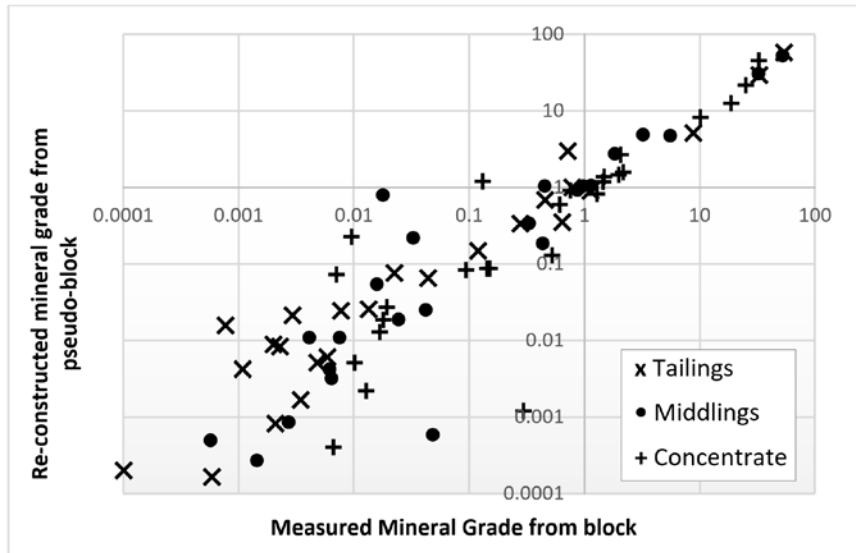
Figure 8. Results of using Model Part B to predict the mineralogy of products of a rougher spiral at a wolframite mine site.

An artificial vision system was developed to monitor and control a wet shaking table. The system determines the position of the dense mineral concentrate band using a camera to monitor the table. Currently, visible light band UV fluorescent vision has been developed for scheelite ore (Figure 9). Infra-red and x-ray fluorescence are under development.
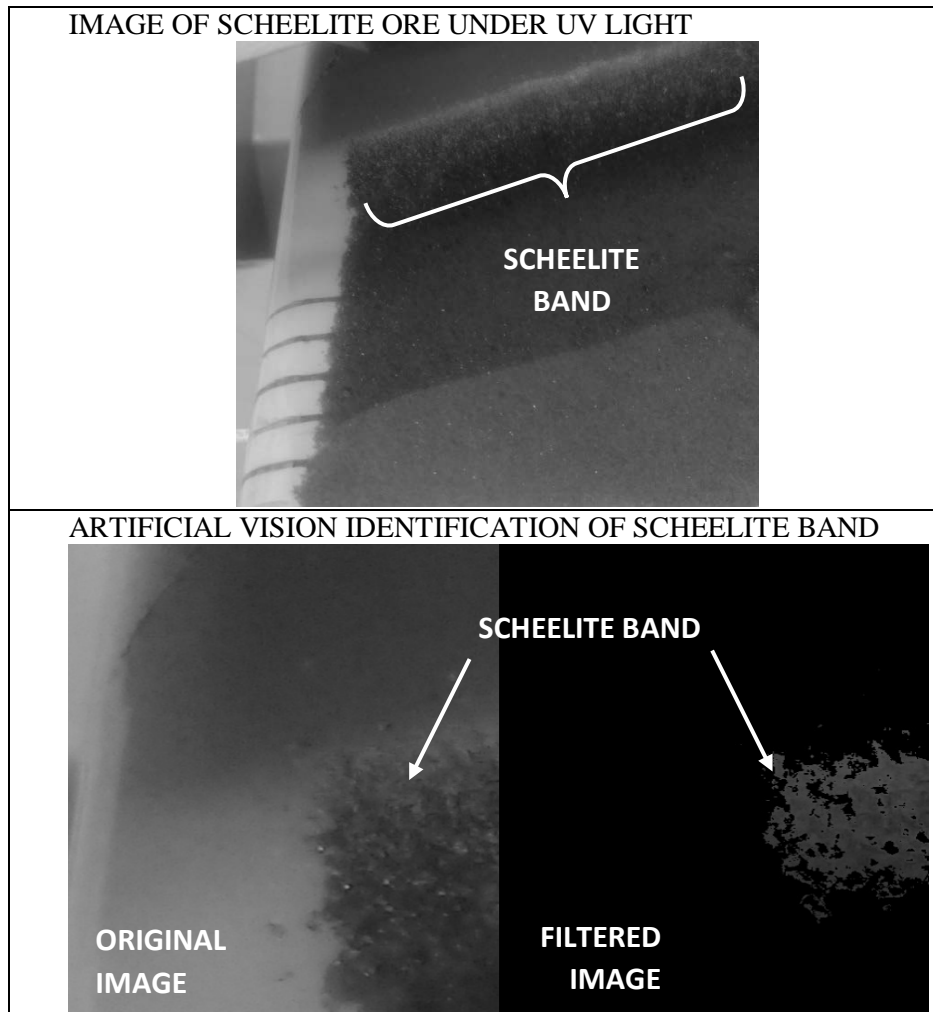
Figure 9. Visible light and UV fluorescence for scheelite ore on shaking table.

The designed system captures hyper spectral data which is used to adjust the product splitter to automatically capture the concentrate band using a linear actuator. A prototype has been developed and will be tested at the OptimOre pilot plant in September 2017 and on a mine site in November 2017. The proposed system is relatively cheap to implement and allows for monitoring of multiple tables. Any movement in concentrate band position caused by changes to upstream processes (e.g. spiral splitter position, grind size) can be corrected for automatically. The system ensures that optimal performance is maintained on each table without the need for constant operator monitoring. Use of hyperspectral data has been researched to increase the applicability of the system. For example, quantitative mineralogy and electron microprobe analyses has shown that hematite is highly associated with wolframite in the Drakelands mine (Fitzpatrick et al 2017). Within the Drakelands processing plant the unit operations which are most effective at separating these minerals are shaking tables. However, control of the tables to optimize the separation is difficult as there is little visual difference between the two minerals (see Figure 10).
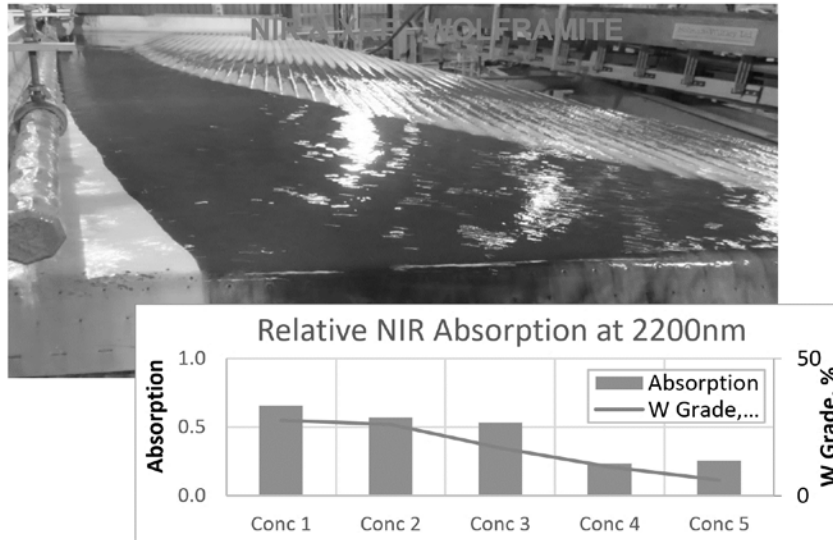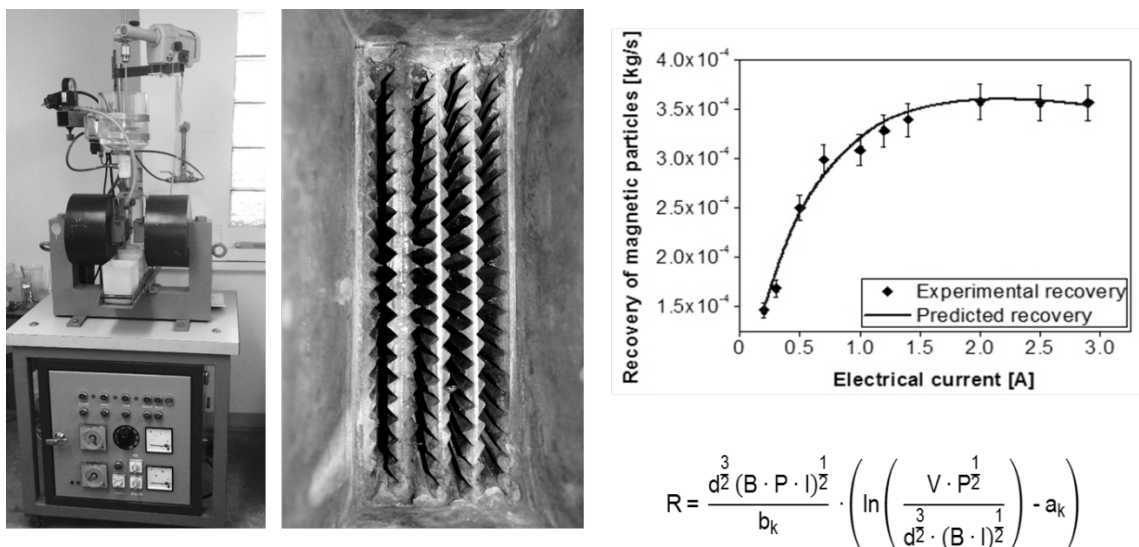
Figure 10. Visual and NIR response of wolframite on a production shaking table.

Samples collected along the concentrate edge of the shaking table in Figure 10 show a wide variation in grade but little difference in colour (i.e. absorption of visible light). When absorption in the near infrared (NIR) region of the electromagnetic spectrum is measured, it can be seen that there is a significant and measurable difference. Visible light response can be used to differentiate wolframite minerals from the table surface and from other gangue minerals so by combining the visible light and NIR data there is great potential to allow for table control to optimize the separation process.

Magnetic Separation

The experiments with high and low magnetic field strength were made in the WHIMS with a working area between 290 and 1100 mT (Figure 14). The matrix is shown in Figure 14, and the tests were working with the Penouta Ta-ore. The equation for this modelling includes the introduction of the magnetic field B, the pulp density of the material-water-mixture P, the electrical current I, and the flow rate V of the pulp through the funnel exit. Figure 14 includes the magnetic model and the graft with the experimental and simulated data.

$$R = \frac{d^{\frac{3}{2}} (B \cdot P \cdot I)^{\frac{1}{2}}}{b_k} \cdot \left(\ln \left(\frac{V \cdot P^{\frac{1}{2}}}{d^{\frac{3}{2}} \cdot (B \cdot I)^{\frac{1}{2}}} \right) - a_k \right)$$

Figure 14. WHIMS and matrix used in the tests. Magnetic model and graft for the Penouta Tantalum ore.

The maximum error between the calculation and the experiments results is 5.8%, a substantial improvement taking in account that the established models have an error up to 20% (Tucker 1994) (Tucker & Newton 1992). Currently, the susceptibility is included, also the model is verified with different matrixes and other material.

For the experiments with the drum separator (similar to the production in Penouta) a new machine was ordered and installed, the working area is between 180 mT and 370 mT magnetic field strength. The iron oxide recovery improves to 5.48 % of the iron oxide in the feed material, (with 370 mT).

With lower magnetic field strength (180 mT) only 2.7 % of iron oxide in the feed material is recovered. The tantalum content of the magnetic product with different field strengths is between 0.05 wt.% and 0.07 wt.%, which corresponds to 0.33% and 0.71% of the tantalum contained in the feed material. I is shown, that the low intensity drum separation is not recommendable for the cleaning process, since the iron oxide recovery is too low (Figure 15).
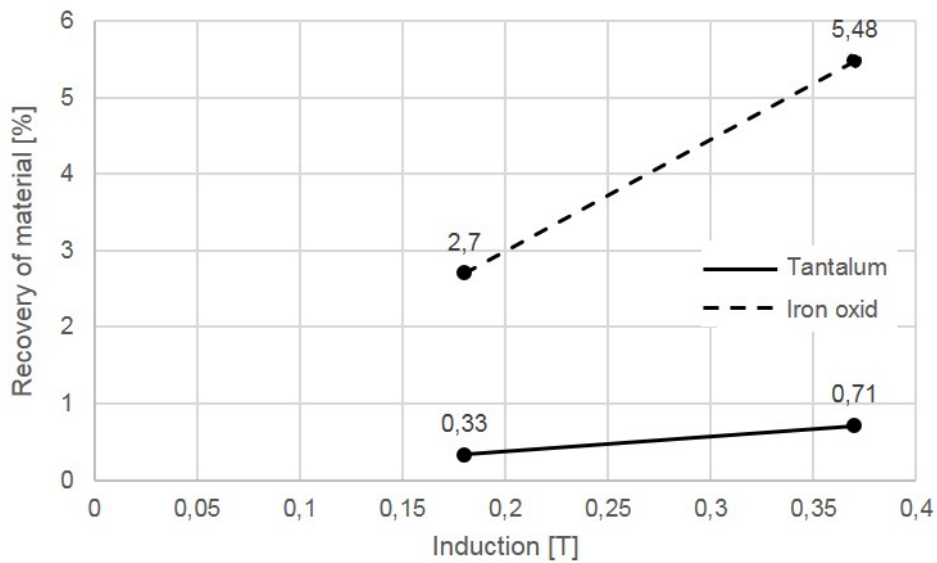

Figure 15. Recovery magnetic particles in the Penouta tantalum sample using a drum separator.

A completely new FEM simulation model for the WHIMS matrix was created (Figure 16).
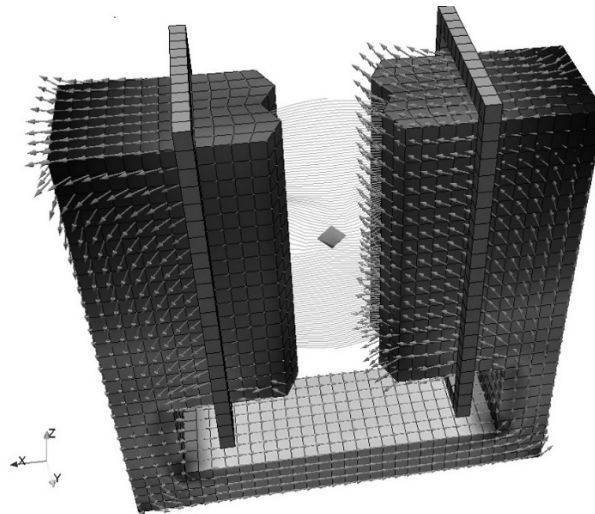

Figure 16. The new FEM model.

The new FEM model allows to change the material of the particle (Figure 17), the medium around the particle and the forces of the magnetic field strength. The individual behavior of the particle can be simulated by using different materials. Currently, the simulation framework comprising multiple particle of different material and sizes is being developed.
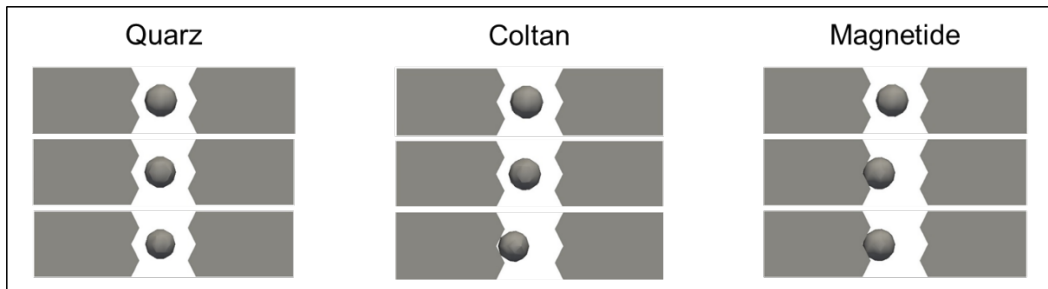

Figure 17. Behaviour the motion of the particles in the new FEM model.

Froth flotation

Froth flotation is focused on the development and evaluation of a predictive approach for froth flotation equipment and reagent regimes commonly used for the beneficiation of typical tungsten and tantalum ores. Froth flotation has been subjected to modelling since the 1930s and there are a great variety of approaches and subsequent models that tried to portray the entire process. An extensive summary of existing models has been established in the first phase of the project.

Two different models of flotation rate constant k are being used and compared: the Pyke model (JKMRC) (Pyke et al. 2003) the Yoon model (Virginia University) (Yoon et al. 2012, 2016). The first model makes use of the generalized Sutherland equation collision model (Sutherland 1948), the Dobby-Finch attachment model (Dobby & Finch 1987) and its own stability model whereas the second model considers an extended DLVO approach for the attachment and stability. Even though the approaches differ, the two models do have common parameters.

With this in mind, the project has focused on using said existing models but simplifying them for optimum use and incorporating in-depth mineralogy information, e.g. mineral surface liberation, particle size and particle shape, as provided by Mineral Liberation Analysis (MLA).

Reagent regimes for tungsten ores has been a critical point of the project, as the tungsten industry struggles with calcium-bearing minerals contaminating a scheelite ($CaWO_4$) concentrate. New reagents, in particular depressants developed in the last five years, have been investigated, showing a decrease in calcite recovery up to 20% and multiplying the grade by 2 to 3 times compared to normal procedures (Figure 18).
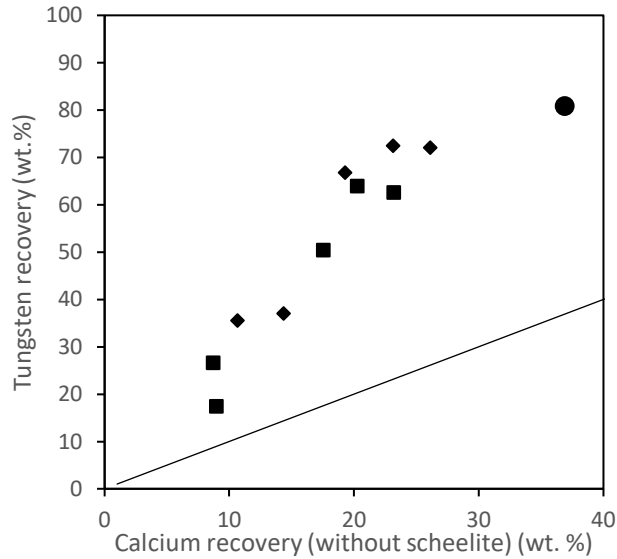
Figure 18. Selectivity diagram of two new depressants (rombs, depressant 1, squares, depressant 2) against calcium-bearing minerals (in black, the selectivity line, the black point represents the reference point without depressant).

Furthermore, in terms of reagent regimes, project looked at the impact of the pH modifier in use and its interaction with classical depressants in scheelite flotation, namely sodium silicate and quebracho (a tannin extract from a tree). The type of pH modifier in use is highly impacted by the depressant and the assumed idea that sodium carbonate limits the amount of Ca^{2+} and Mg^{2+} ions in the pulp thus improving scheelite flotation is probably ill-founded for calcium but correct for magnesium (Figure 19).
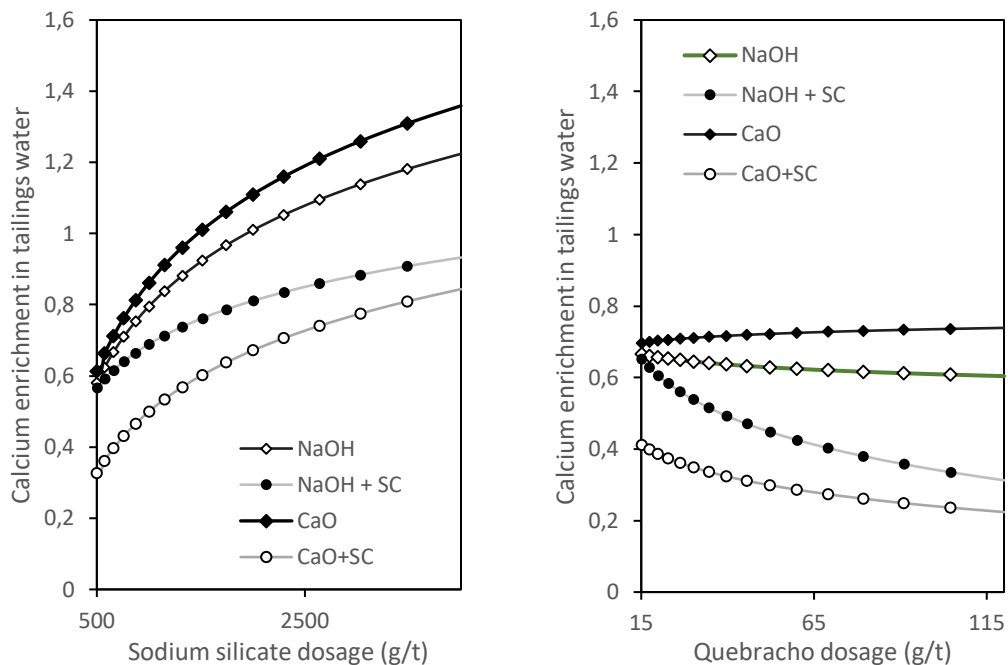

Figure 19. Ca^{++} enrichment in the tailings water of flotation compared to their content in the flotation feed with sodium silicate (above) and quebracho (below).

Process control system

The OptimOre project has created an active monitoring system of the process flowsheet to detect variations in system behaviour that have the potential to affect the expected mineral recovery. This is coupled with an advanced expert system that will propose the best parameter adjustment according to the process state. More specifically, the idea is to monitor key parameters in each process stage considered in the project (crushing, milling, gravimetric separation, magnetic separation and froth flotation), and based on the information extracted from sensors, determine the best course of actions to overcome it using the developed models reported above.

Regarding the control system, there are two main objectives: 1) to determine the current state of the process based on the information provided by the monitoring system; and 2) to determine any fault, misbehaviour or misadjustment occurring in the process. The first objective not only focuses on the installation of suitable sensors, but also concerns the development of control charts to inform, in a visual way, of the state of each process block (crushing, milling and gravimetric, magnetic and froth flotation separation).

To validate the different models developed within the OptimOre project, the monitoring system is being installed into a pilot plant located in the UPC installations at Manresa, which will also be key to adjusting and improving the expert system, described in the next section. Currently, we are working on the monitoring system of the pilot plant, which also includes a newly developed sensor and software capable of determining the particle size distribution in terms of particle size and grade for Scheelite.

With regards the expert system of the OptimOre project, its main objective is to suggest the best parameter adjustment to correct any deviation from the expected recovery, and/or to readjust the process operation to minimise the impact of variations in material fed into the process and along each stage. More specifically, and based on a series of experiments, a "target region" with the best operating conditions is defined. Using the information provided by the monitoring system, the status of the process is determined, and based on the region where the current configuration lays, the expert system will suggest the parameter adjustment that will improve the mineral recovery to the desired region. The suggested action will be the one that requires less adjustments to avoid causing an abrupt change to the elements found after the unit whose parameters will be adjusted.

Let us exemplify the procedure by showing the process configuration space obtained after several experiments with a shaking table depicted in Figure 20. In this figure, both the concentrate grade ratio (y-axis) and the tailing grade (x-axis) are a function that takes into account the concentration of particles in the concentrate and tailings respectively with respect their accumulated mass. More specifically, we want high concentration values of particles in the concentrate with low masses (we are working with rare materials, so we expect to recovery a low percentage of material), while on the other hand, we want in the tailings a lot of material (high mass) with a low concentration in each particle. Therefore, our "target area" is on the upper right region in Figure 20 (filled area).
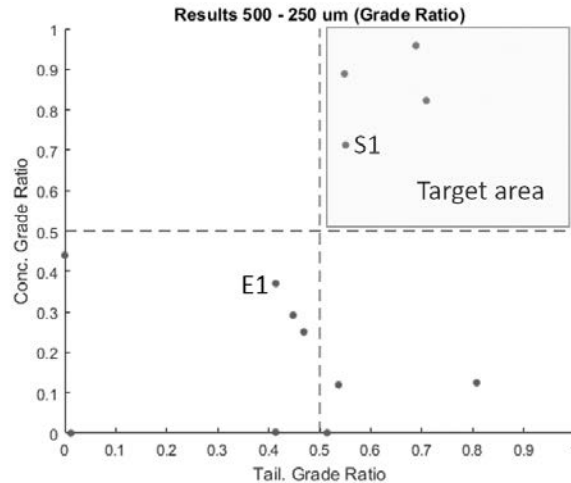
Figure 20. Process configuration space for a series of shaking table experiments and the target area within this space (filled area).

As can be seen, in this case there are 4 experiments that landed in this region, and therefore, the system will take their configurations as the optimum operating conditions. Whenever the system has a new observation that lays out of this region (for example E1), it will look for the past case within this target area with the minimum differences in parameter settings, which in this case would be S1.

Currently, we are working on defining the series of experiments that will allow us to fix the target area for the pilot plant configuration, and that will also serve as the basis of the expert system (base case).

Knowledge transfer and validation

In parallel to the technology research, the knowledge transfer was carried out during all project, the permanent contact with the companies allowed to do the transfer of knowledge. For example: the results from mineral characterization and grinding processes with tantalum ore has been transferred to the Penouta mine (tantalum mine), the gravity separation results using the Hemerdon material were transferred to Wolf Minerals (tungsten mine) and the froth flotation results were presented to the Mittersil mine (tungsten mine).

The project is progressing on the development of new information systems for real-time decision making and dynamic simulation of the integrated processes. It is planned to begin validation trials at a number of industrial sites in the next few months. In preparation, bench mark simulations of existing flow sheets have been prepared against which to test the benefits of selected process enhancements. These will be validated in a project-specific pilot plant before to be applied to industrial plants. The overall integration and validation strategy is shown in Figure 21.
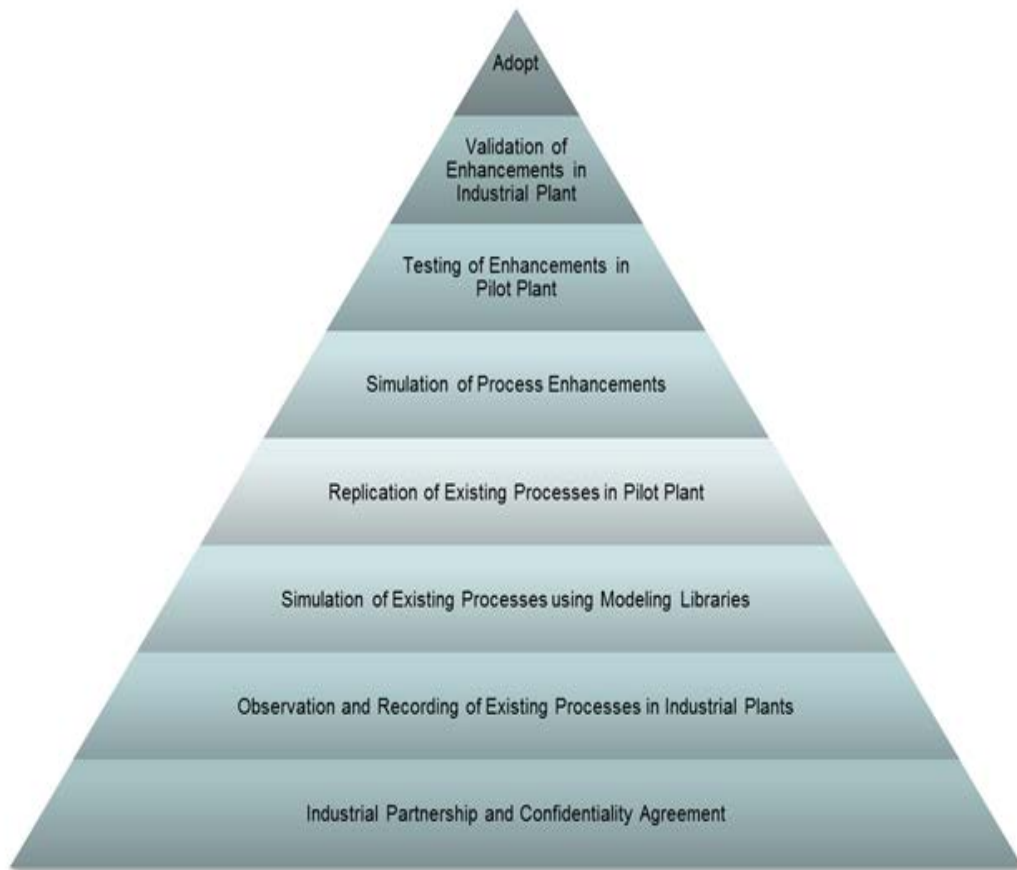
Figure 21. Validation Strategy followed in the Optimore project.

The strategy ensures that outputs of the project can be clearly demonstrated in an industrial setting and ultimately are adopted by the project developers and mineral producers themselves. A progressive mechanism to secure this aim has been developed to generate increasing confidence in the project results. At the time of writing this document, dynamic simulations of the proposed validation sites and the pilot plant have been prepared for the following:

- Pilot Plant – UPC Laboratory, Manresa, Spain
- Mittersill Tungsten Mine (Underground) – Mittersill, Austria
- Drakelands Tungsten Mine (Surface) – Hemerdon, UK
- Penouta Tantalum Mine (Surface) – Viana do Bolo, Spain

Although individual project partners are using a variety of simulation techniques for their research, the integrated simulations are being prepared using Object-Oriented modeling. This is a fast-growing area of modeling and simulation that provides a structured, computer-supported way of doing mathematical and equation-based modeling. Modelica is today the most promising modeling and simulation language in that it effectively unifies and generalizes previous object oriented modeling languages and provides a sound basis for the basic concepts.

Integration of the various modeling systems used on the project (Matlab, Simulink, etc.) will be used via the use of the Functional Mock-up Interface (or FMI), which defines a standardized interface to be used in computer simulations to develop complex cyber-physical systems. Most advanced simulation systems provide FMI import-export functions that enable model components developed in different environments to be integrated and run as one model (Figure 22).
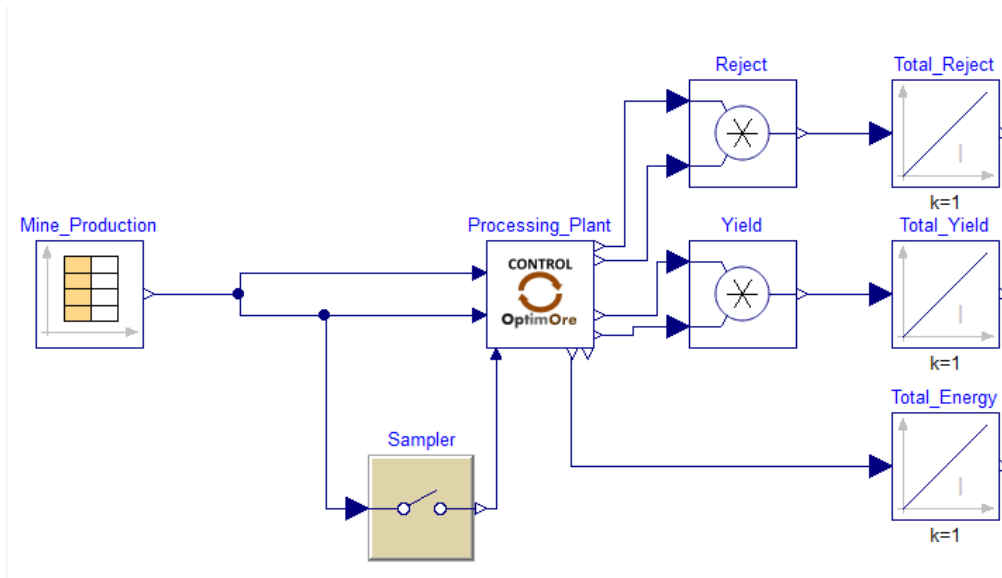
Figure 22. Simple Dynamic Model.

This type of dynamic simulation models can be run over any interval of time to emulate the physical system that they are simulating. For example, in the case of industrial systems at the project reference sites calibration of the models was typically carried out over a year to ensure that the performance of the digital model matched that of the industrial plant.

The complete range of technological advances developed by the research partners will be evaluated in varying combinations as illustrated in Figure 23. No single industry site exists that covers all of the technologies that are the subject of the OptimOre research so different work packages have been assigned to each technology.
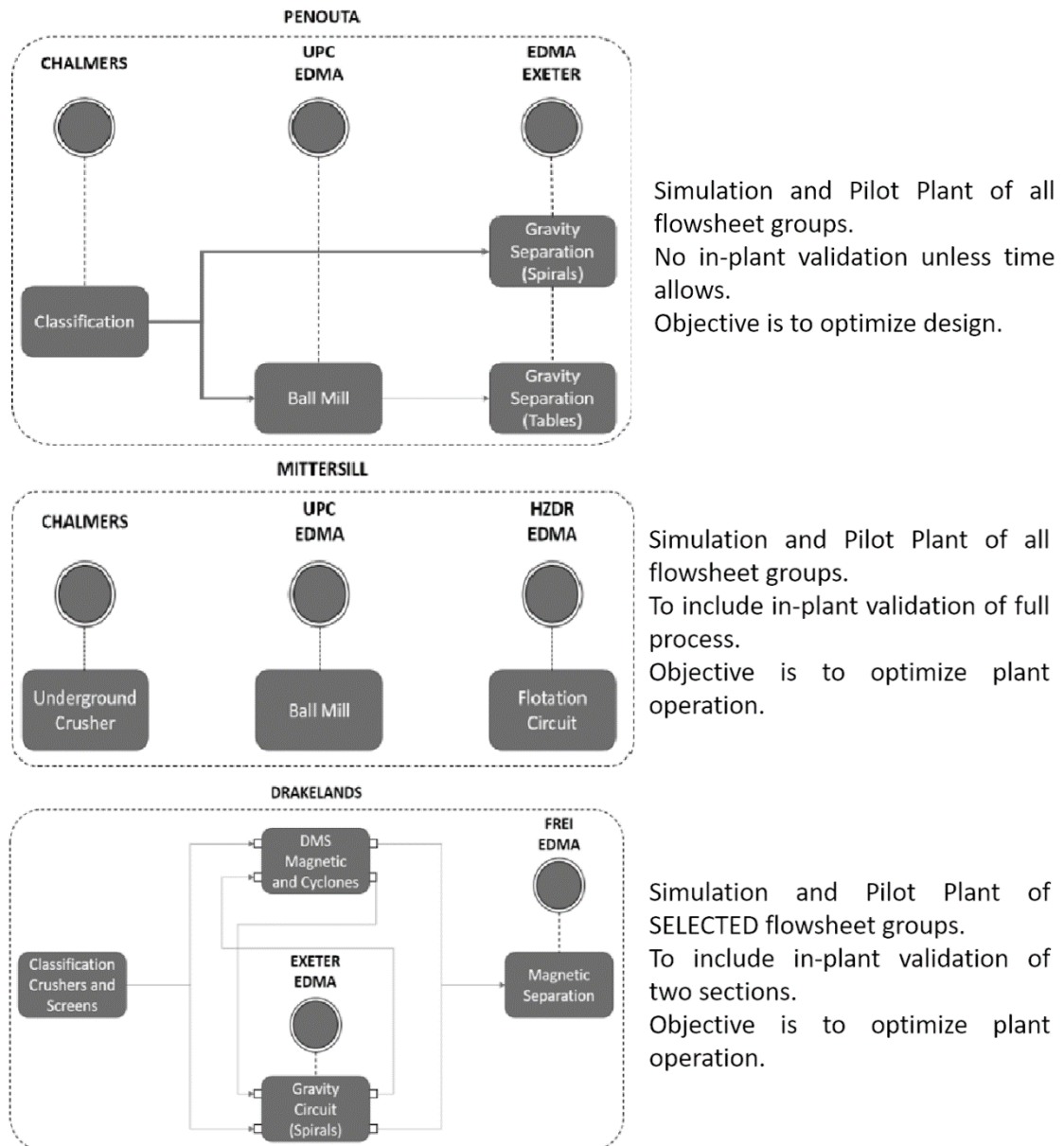
Figure 23. Scope of Industry Validation.

Conclusions

In the OptimOre project models for crushing, milling, gravity, magnetic and froth flotation separation were developed for Ta and W ores. A new control system was developed in the latter part of the project, using the process models from the previews part and advanced sensor systems. Validation in the simulation environmental has been carried out and pilot plant and the real plant validation is planned for the end of the project. The knowledge transfer is being produced along the project between the Tungsten and Tantalum industry and the project partners as a consequence of a strong relationship between both.

This project will provide a necessary step in order to increase the competitive of mining industry in the mineral processing field. The advanced control using a deep knowledge of the processes will be an opportunity for the EU mining companies in order to increase their competitiveness and improve the mineral recovery and then, to increase the Tantalum and Tungsten reservoirs in the EU.

Acknowledgements

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