Project: Opening up Natural Resource-Based Industries for Innovation: Exploring New Pathways for Development in Latin America

CASE STUDY | Laboratory of Geomechanics for Mining

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September 2012

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1. Introduction

This report corresponds to the findings of one of the four case studies conducted in Chile as part of the project "Opening up natural resource-based industries for innovation: Exploring new pathways for development in Latin America". One of the types of "alternative pathways" we are interested in are "path-creating" alternatives, i.e. those that start from the needs and experience associated to natural resource sectors, but involve innovative, knowledge-intensive activities that can help develop national technological capabilities.

The lack of collaboration between universities and mining companies has been a recurring theme during our study, and one of the cases we analyzed is one of those exceptional situations where these two collaborate productively in advanced applied research. The rock burst phenomenon is one of the worst risks in underground mining operations, and a better understanding of it would produce two very important improvements: avoiding deadly accidents and allowing for a higher rate of mineral extraction. Codelco División Teniente and a research group at the Center for Mathematical Modeling at Universidad de Chile have established a rich collaborative relationship that has been working on this problem for many years already.

The report starts by describing the methodology and the two groups that are the focus of this case. First we look at the institutions where they are located, and then go in more detail about them and what they have been doing. After these introductory sections, we analyze the five main questions of our study:

1. *How widespread has the alternative become?*
2. *How distant is the alternative to the dominant trajectory?*
3. *To which extent is the alternative promising or delivering better outcomes?*
4. In which ways has the availability of internet and/or other ICT technologies contributed to the development of the alternative?
5. Which are the main barriers that block the diffusion of the alternative?

Finally, we present a summary of our findings for these questions.

2. Methodology

As for all the cases under study, we base our work on both secondary information and primary information obtained from interviews to key informants. While the secondary information was fundamental for the previous stage of the project, where we described the dominant trajectory and its problems, in this stage we base ourselves on the primary information and

follow a case study methodology (Flyvbjerg, 2006). However, we still use some secondary information for the general description of the case, as well as for contrasting the official available information to that obtained from the interviews.

We focus the study on the issues discussed in the Consolidated Paper (Marin and Benavente, 2011) that summarizes our adaptation of the Transitions Framework to study the problems of sustainability and generation of diversity in Latin American economies, starting from natural resources.

We conducted interviews to CMM researchers, their counterparts at Codelco, and other actors that have knowledge about the interaction between Codelco and university researchers.

We used the software QSR NVivo 8 to analyze the data collected. We coded different fragments into concepts, research questions, and actors. This allowed us to later produce queries that crossed, for example, research questions with different important concepts of interest, to easily analyze our data but to do it in a very thorough way.

3. Context

3.1 Center for Mathematical Modeling

The Center for Mathematical Modeling (CMM) was established in April 2000, building on the experience of a group of researchers at Universidad de Chile's Department of Mathematical Engineering, that had been working on applied mathematics projects on different research areas and collaborating in multidisciplinary projects.

The initial counterparts for the CMM were the French *Centre National de la Recherche Scientifique (CNRS)*, Universidad de Concepción, other Departments at Universidad de Chile, Codelco and Dassault Aviation.

The Center's mission is *"to create new mathematics and use them for solving problems of other sciences, the industry, and public policies"*. They envisage themselves as a world class center on research and training in advanced applied mathematics, *"recognized as a platform for industrial mathematical modeling with high innovation impact"*. To achieve this, they focus on areas where there is a *"real possibility"* to become an internationally recognized leader. Although the Center says to promote interaction between its participants, it is not clear to what extent this happens in practice.

The collaboration with CNRS has been important to validate its research quality, creating a joint research group. FONDAP funding[1] was fundamental for the initial establishment of the center as well as its continued existence, and Universidad de Chile also made a bet by giving special funding to this center.

Codelco and Dassault have had two important roles: providing funding for the center, as well as being industrial counterparts to develop high-impact research projects. Many other national and international counterparts have later worked with the center, including private firms and ministries.

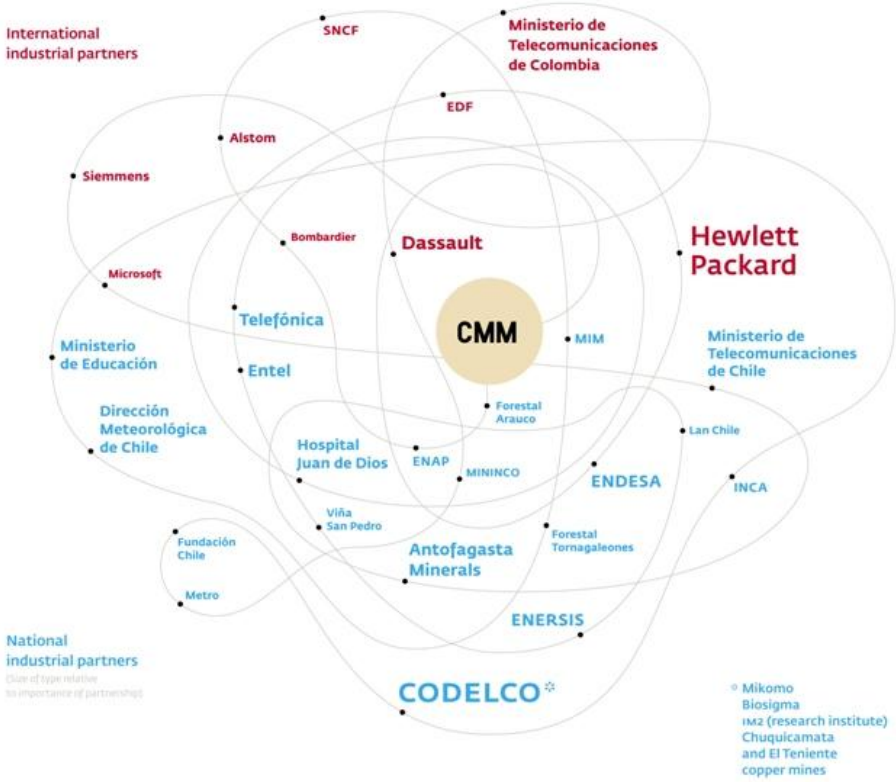

Figure 1: CMM and its counterparts

The CMM has had 40 researchers, over 90 visitors and over 40 PhD students, published over 90 articles in ISI journals, and participated in many international congresses. The center has been granted one patent, and another is being reviewed.

Some of the areas of where applied research has been conducted include transport systems, regulated services' tariffs, mining (several different problems), medical diagnosis, forestry, and fishing resources management. There are laboratories established in several areas, including

[1] FONDAP is a CONICYT funding line oriented at articulating the work of researchers in areas where national scientific efforts have already achieved high levels of development.

image visualization, bioinformatics, mathematical modeling in mining, and stochastic simulation.

3.2 Codelco División Teniente

El Teniente, located 80 kilometers South from Santiago in the O'Higgins Region, and at 2,500 meters over sea level, is the largest underground copper mine in the world. There are reports of copper extraction already in 1819, and its continued exploitation began in 1904. It has over 2,400 kilometers of underground tunnels. El Teniente is producing around 400,000 metric tons of fine copper and 5,500 metric tons of molybdenum. It represents almost 25% of Codelco's production.

Its formal operation in 1904 began as Rancagua Mines, but soon changed names to Braden Copper Company. In the 1940's the technique of "block caving" started being used for extraction. In 1967, in the context of the "Chilenization of copper", the State acquired 51% of the company, and the name was changed again to "Sociedad Minera El Teniente S.A.". In 1971, the "Nationalization of copper" meant the expropriation of the remaining private participation in the company. In the 1980's, as high grade ores began to run out, new extraction techniques started being used (i.e. panel caving, using mechanized equipment).

Teniente was the scene of one of the most dramatic mining accidents in Chilean history: the "Fume tragedy", when 355 workers died suffocated with carbon monoxide in 1945. The results of this tragedy were that the company became a leader in safety issues and a significant change in job safety regulations.

4. Laboratory of Geomechanics for Mining at the CMM

In 1982, underground exploitation in El Teniente mine arrived at deeper and harder rocks, and with these the phenomenon of "rock bursting" appeared. The rock is fragile, and it can suddenly explode and project material in all directions, similar to glass being broken. The effects of rock bursts can be dramatic, the worst of several accidents since that date was in January 1990, with seven dead miners and many more who stayed trapped. People that work at mines remark how dramatic these situations can be for everyone: those trapped inside, and those outside, including co-workers and family, who might not know for several days if those trapped are alive or not.

The effect of that accident was radical in the mine. The previous long term plan was dismissed, and there was a complete rethinking of how mining ought to be done, asking themselves *"if this was the right way to conduct mining"*. The result of these reflections was to understand mining as something conducted by men, rather than something that simply happens. Or in other words, to be much more careful about how the mountain is carved, applying (since around 1995) different process control techniques. In practical terms, this means that mining is

not conducted as fast as possible, and rather as fast as it can be done safely, to avoid repeating accidents like that of 1990. Besides the dramatic human aspects, another accident like that could mean temporary or even permanent paralysation of the operations, something with a significant economic impact on both local population and national income.

Currently, technology and ideas are not enough to increase the mining pace safely, the operation would need an important technological breakthrough to dig safely the large reserves of copper that are contained in deeper rocks. And even if no radical breakthroughs emerge, it is desirable to understand as much as possible how the rock works, why and when there could be bursts, so as to increase at least marginally safety and/or extraction speeds. This is where the "Rock Mechanics" group comes in. This group is conformed of around 30 engineers, five or six of whom are exclusively dedicated to research. The rest work on the daily operation, as the group is responsible for both the operation and the research in their area. And the Rock Mechanics group at El Teniente has been working closely with CMM researchers for about a decade.

Our study focused specifically on the Laboratory of Geomechanics for Mining (founded in 2008), which is the formalization of the work that was being conducted by the CMM and the Rock Mechanics group at Codelco's Teniente Division. We focused on one specific problem worked at the CMM to have a rich, in depth understanding of how (successful) interaction between university researchers and mining companies works. Moreover, the problem we studied is one of utmost importance for underground mining, called by some *"the mining of the future"*.

The collaboration between the CMM's Geomechanics for Mining Laboratory and Codelco División Teniente has been in the form of projects developed by the Geomechanics group to Codelco-Teniente, which acts as the client. This is important for the way the relationship works; *"we are clients, if they don't please us, there is no contract"*. For the past 10 years or so, different projects have been developed, always on the rock bursting problem. It started with some informal contacts, there was a project used to *"get to know each other"*, and currently they engage in a rich collaboration that is an example of how universities and industry can collaborate in applied problems.

Initially, it was necessary to develop trust in each other on the one hand, and the ability to *"speak the same language"*. This was something critical. Considering how abstract mathematics can be, it is not trivial for other professionals to work with them. At the same time, the mathematicians had to understand the mining process, and the engineers had to understand how mathematicians think and speak. There were three fundamental aspects that made it possible to overcome these barriers and keep working together: both sides were open to understand the other, understood each others role, and finally, a mathematical engineer had been part of the Rock Mechanics team (since 1988). He has proved to be a key connection in making communication between the two groups possible.

After the initial projects, there has been almost constant work together for almost a decade, in many relatively short projects (most of them lasts less than a year) that have succeeded each other. The mathematicians understand the importance of the problem and are glad to be working on it, and the engineers are deeply interested in the mathematician's work, something that is manifest in the weekly or bi-weekly visit from Codelco's engineers to the mathematicians in Santiago, that usually result in several hours long meetings, where ideas, advances and problems are openly discussed. These work dynamics are not the norm in university-industry relations, and not even the norm for the CMM. And as someone stated, *"if it wasn't every week, we would get nowhere".*

The work done by CMM researchers have been described as being at least as good, if not better, of what is being done in the area internationally. The Geomechanics group is leaded by researchers from the Mathematical Engineering Department that have worked together with academics from Physics, Geology, Civil, Mining and Mechanical Engineering, as well as engineers and students from different universities. There are currently four active researchers, three external collaborators, and fifteen other researchers have participated in the previous projects. One of the main outputs of their projects are computational tools to assist decision making in underground mining planning. For example, software to estimate the "maximum stable cavity" in a rock, using a particular mathematical method, or software to estimate and visualize the mechanical efforts induced on rocks by underground mining.

5. Q1: How widespread has the alternative become?

Following our adaptation of the Transitions Framework, described in the Consolidated Paper (Marin and Benavente, 2011), we describe the diffusion of the alternative in terms of networks, expectations, learning processes and policy initiatives.

5.1 Networks

Although the case's actors can be reduced to two, the Geomechanics Laboratory and Codelco-Teniente, they are inserted into a broader context. The lab is a part of the CMM, which is based at the Mathematical Engineering Department of Universidad de Chile. Codelco Division Teniente in turn, is one of the main divisions of state-owned Codelco, the largest copper mining company in the world.

The CMM's reputation and connection to the University has been important in having researchers available. The interaction with other CMM laboratories and research projects has not been significant, although the geomechanics group does have members from other universities and other departments from Universidad de Chile. The researchers that have been trained at the group and later leave could become important in the future, probably not for

this particular research subject, but for the development of other groups that perform similar applied mathematics research.

Codelco-Teniente, on the other hand, has a group of highly qualified and experienced individuals, with a team leader that is interested in the possibilities provided by university research on mathematically modeling the rock bursting phenomena. Working with a prestigious university and research center is positive for Codelco in terms of its image, and we can see in the quantitative report that Codelco and Universidad de Chile have a very strong relationship.

But besides the people involved at both sides, this area of development has been totally circumscribed to the Geomechanics Laboratory and Codelco-Teniente. There have been contacts from foreign companies and consultants to the research group, but they feel they simply want to "use" them. On the other hand, there have been weak attempts by former CMM members at establishing private companies that develop similar research. But these attempts at competition have not persevered, mainly because of the lack of enough mathematical expertise, only possessed by senior researchers. The Geomechanics research group has attempted contacts with other Codelco Divisions, but the group is currently constrained by the amount of researchers.

Codelco (more precisely, the Rock Mechanics group at Teniente) has attempted to *"show to the world"* the work from the research group, but this has been difficult due to the previously strict company policies regarding intellectual property and diffusion of results (there are reports of bad experiences that Teniente has had with external actors and property rights). Nevertheless, both senior and younger researchers have made international –and probably national– contacts during their work on these projects. There was recently an important change in the official position from Codelco, in terms of allowing the diffusion of research results[2], that has resulted in papers submitted to international congresses.

5.2 Expectations

There is potential for several important developments associated to these research projects.

First of all, as ore grades decreases, it is expected that Codelco –and later other companies– should start doing underground (rather than open pit) mining. As this happens, the expertise of this research group will be highly valuable. But for the case of Codelco, it is not clear *when* the jump to underground mining will take place in some of their operations, as deadlines seem to be highly dependent on individuals. And as mentioned above, the group is currently somewhat constrained, and it would not be easy to grow in the scope and number of projects

[2] It is not clear why this happened, it might be associated with the arrival of groups that will be doing research in mining in Chile, as a way to show that important and advanced research is being conducted at Codelco.

being worked on. Moreover, it is risky for the group to begin work with other mining teams, as the same high-quality working dynamics, that are characteristic of this collaboration, might not be replicated. However, it is clear that if the group wants to sustain its research line in time, it cannot rely exclusively on one of Codelco's Divisions.

Second, and related to the first, there is also codified knowledge, and the same problems exist or will exist in other countries (e.g. Australia). Some of the projects' outputs have been software applications that could be adapted to use in other mines. What is not clear is what stance Codelco will take, as their policies on this respect have been oscillating. There is clear potential for doing business with the research that they have been funding, but Codelco's worries lie with maintaining their production levels (*"we earn money selling copper"*), and the eventual commercialization of their research results is absolutely secondary. At the same time, the researchers are interested in their research, and not in the additional worries and demands from developing a marketable software solution (such as commercialization and support). A broker would be necessary to turn these research projects into products that could be adapted for other mining companies and sold to them.

The team at Codelco sees potential for the geomechanics group to obtain international funding and collaborate in international research groups, as well as for obtaining domestic public funding to support their research. They are willing to help position this research group internationally, but the attitude of the group toward these possibilities is not clear.

The CMM gives researchers on mathematical engineering a unique opportunity of working very close to actual industrial problems. Another interesting future prospect is the development of consultant firms by researchers that have been formed at the CMM, and the incorporation of these researchers in other productive sectors. This has only happened in a small scale now. Most tend to go to universities, and private firms are for the most part not interested in having researchers. But there are different policy initiatives, together with the increasing awareness about the importance of entrepreneurship and innovation that could change this.

5.3 Learning processes

Two different learning processes can be observed in this collaboration relationship. One is the generation of knowledge in the research area itself. The other is second order learning associated to the collaboration.

Codelco Teniente had a team that worked on the rock bursting issue, which since 1988 had a mathematical engineer. Initially, it was necessary to understand the problem at hand and formulate the questions. Later, work with the CMM started (around 2002) and made it possible to progress along the lines of mathematically modeling the rock bursting problem. Since then there have been many projects among the two groups (that at the CMM and that at Codelco-Teniente), all in the same direction. Nevertheless, there is still much work to be done in the subject.

The collaboration between the CMM team and the Codelco-Teniente team was in great part made possible by the existence of a mathematician in Codelco's team. Mathematicians are highly abstract in their thinking, and it is not trivial for people with other backgrounds to work with them. First it was necessary to *"speak the same language"* and after successfully doing this, it was possible to develop a remarkable collaboration dynamic between the two groups, that has been key for its success. The mathematician at Codelco is still fundamental in having fluid communication between the two groups though.

However, this learning about the problem, and the learning about how to work together, has occurred inside this bilateral relationship, closed for the most part to the rest of the mining and research communities, and even collaboration with other departments inside the university is not too strong. Particularly, there have not been many spillovers to the university, for example through courses, because of the researchers' time constraints. This research group has worked as an isolated, rather than network-based niche.

5.4 Policy initiatives

There has not been an important interaction between public initiatives and this case. Maybe the most relevant is that public funds (FONDEF projects were mentioned) could be an important way of giving more financial stability to the research group. They currently depend on relatively short-lived projects (few last for a year), so financial continuity (especially for younger researchers) is a problem. However, Codelco indicates that they motivate researchers to apply for these funds but they have not done it. On the other hand, they seem worried about loosing Codelco's group interest if involved in a longer term project (besides, Codelco would stop being the owner of the project if it has public funding). They have also seen other CMM groups obtain FONDEF funding, apparently without very positive results.

There are some issues that were mentioned in this case that could be seen as important for the diffusion in general of this kind of collaboration relationship between universities and mining companies.

Related to Codelco, being a public company, there are sometimes important levels of bureaucracy to release funds (*"a single signature can take up to three months"*), something that can complicate researchers. It is also a problem that individuals in key positions can be changed after government changes.

Another relevant fact is that Codelco is less interested in public funding than private companies: it is the same public money that goes from one place to another[3]. On the other hand, relatively recent public initiatives that could be important for these collaboration agreements are the tax credit for R&D and a subsidy for hiring PhD's in private firms. The

[3] This is particularly evident in the case of tax incentives, as all of Codelco's profits go to the State in any case.

former can be a good incentive for private firms to work with universities (as they get funding but still lead the projects), and the latter can help insert the researchers trained at the CMM in other companies or even industries. These two initiatives could be important for the future of these initiatives, although up to now there has not been much interest from private agents.

Summing up, the initiative has had limited connection to other actors, although this might be changing with the attitude change from Codelco's officials toward secrecy. There has been significant learning in terms of the knowledge produced and the way to work together, and the expectations for the expansion of the initiative are significant, because of the future perspectives for the sector in terms of underground mining. Moreover, there is potential to commercialize the results, and there is also significant potential for spillovers to the rest of the domestic economy in the form of applied mathematical modeling in other sectors, as well as demonstration effects for other mining companies and economic sectors. In other words, it can promote the rise of other niche-like projects, although this still has to be materialized.

6. Q2: How distant is the alternative to the dominant trajectory?

Considering that this is a path-creating alternative, it is not simple to compare it to the dominant regime. The comparison is not "parallel" to the regime, in terms of describing an alternative pathway that achieves similar objectives through different means. Instead, it produces something completely different, and as such, all dimensions are completely different from the regime's, and not always directly comparable. More than speaking of distances between the two in each dimension, we will describe them for the case of the alternative.

6.1 Guiding principles

There are several different guiding principles behind the collaboration of these two entities.

On the side of the researchers, there is on the one hand the interest in doing research, and on the other, the motivation of working on a problem that is extremely important for the country: rock bursts can produce fatal accidents, as well as paralyze production.

On the side of the mining company, there is on the one hand what seems to be the regime's ultimate motivation: maximizing production levels. But there are two differences: for the case of Codelco, all profits go to the State. The other is that the interest of Codelco-Teniente in the rock bursting problem comes from a historic tragedy.

An accident in the 1940's caused around 300 deaths, and this produced a radical change, making security one of the main objectives, with this mine becoming a regional leader in this

respect. They are currently oriented by the philosophy that *"humans can direct the mining process"*. Extraction rates are currently constrained by the mining speed for which there is certainly a very low probability of bursts. They want to avoid at all costs these fatidic accidents, but at the same time, they want to move forward the restriction as much as possible, and that is the objective of geomechanical research.

So in the end, the final motivation is increasing production, just as in the dominant regime, although with the caveats above, most notably the interest in safety.

6.2 Products

The nature of path-creating alternatives, and the reason for our interest in them, is economic diversification. The "products" by the case studied here are not alternatives to copper, but rather different forms of knowledge and technological capabilities.

The work of these groups produces several things:

- Knowledge about the rock bursting problem, which could eventually be codified and commercialized (as software applications).
- Mathematical engineers trained in industry-applied research
- Experience and learning about how universities and firms can collaborate successfully, that can be useful for institutions on both sides. This could also have demonstration effects on other universities and economic sectors that could benefit from doing research but still do not take the leap. Besides its eventual replication, the experience can be useful for the design of institutions and public policies.

6.3 Technology

In this dimension, the technology used by this case is mostly that used by the mathematicians to perform this research. As simply as it may sound, it is papers, pens and software. Most of the value produced comes from their thinking and work on the problems at hand.

We could also consider the institutions or "social technologies" (Nelson and Sampat, 2001) that regulate the interaction between the actors to be important. There is a research center based at a university, methodologies and procedures inside Codelco to allow the funding of this kind of projects, and the way the rich and deep relationship between the two actors itself works. These institutions have been aligned in a way that has allowed this relationship to be fruitful.

The quality of interaction between agents and its associated institutions in the dominant regime is something that varies across situations. In general, the dominant regime does not have good institutions and experience in this respect, and successful cases are the exception instead.

Regarding the technology associated to the extraction process itself, where this research's results can be applied, it is absolutely part of the dominant regime. What is different is that we are talking about an underground mine, and currently large scale copper mining is dominated by open pit mines. Teniente leads in what is going to become the dominant way in the future, when ore grades make it the only feasible way in other large mines. The projects' outputs are meant to support decision making and improve the planning of underground mining, that is performed in a similar way as it has been done historically, except for the fact that extraction speed is limited by what can be considered to be safe and process control techniques are applied.

6.4 Industrial structure

The case under study is the relationship between a mining company and a particular research group. It is inserted into a broader industrial, economic and social structure, but in itself it does not represent a particular "industrial structure". What matters is the collaboration relationship between the two, which is inserted mostly into the dominant regime.

What does differ from the dominant regime and is related to industrial structure, is the fact that in this case, a Codelco Division (El Teniente), and particularly a team inside the division, is responsible for research in a particular area. In general (although we did find other exceptions), it is the Headquarters that guide innovation policy. In this particular case, the reasons is that the rest of Codelco does not –yet– have the problem.

Another issue related to industrial structure is whether mining companies work together with universities at all. As shown in the quantitative report (Benavente et al., 2012), there appears to be a decline in the interest to work with universities, and this has been ratified by the interviews during the case studies. This case of continuous work during 10 years, and that will likely continue in the future, is a notable exception.

6.5 Knowledge

The core of this case is the generation of new knowledge. They are pushing forward the global knowledge frontier, and there is no way to obtain the knowledge from other sources (this is the whole reason for the existence of this collaboration).

The starting points were the tacit knowledge possessed by mathematicians on the one hand, and Codelco's engineers, on the other. One of the reasons why this case has been successful is because both sides have complemented each other well in terms of their knowledge and capabilities, being close enough to be able to collaborate, but far apart enough so that creative ideas emerge (Nooteboom et al., 2007). This is a position that is not the norm in the dominant regime, where researchers use to be too far away and uninterested in understanding the industrial problems, and engineers in the mines are far from universities and don't always see them as having potential to produce usable research.

As mentioned before, eventually the knowledge produced could be codified and commercialized. Formally, Codelco owns the results of the research, but most of it is in the form of software applications that cannot be patented.

6.6 Culture and values

This point is strongly linked to the guiding principles. There are two cultures participating here: that of researchers, and that of a mining company.

What they have in particular is that Codelco is a public company, whose profits go to the State. At the same time, some people inside Codelco (this is definitely not the case at the corporate level) feel that they have a role to play as catalysers of the development of technological capabilities in the country, via their demand for industrial knowledge. This idea is supported by our findings in the quantitative report. At the same time, one of the motivations behind the work on rock bursting, besides increasing production, is avoiding accidents that can be dramatic and result in the loss of many lives.

On the side of the researchers, it is remarkable how they recognize that they are not working on their problem, but on the company's problem (*"It's them who have the experience [...] it's them who dominate this matter, and it has to be that way"*). This seems trivial, but in general the culture of university researchers does not go in this line, some of them actually disapprove it. Part of the explanation for this might come from the fact that they are working in a problem that is extremely important for long term safety and copper production levels. This might provide an incentive that minimizes the fact that they are working on someone else's problem.

Finally, the rich collaboration culture that has been generated between the groups is remarkable, an exception but at the same time an example for other researchers and firms in the country.

7. Q3: To which extent is the alternative promising or delivering better outcomes?

Following the classification used in the Chilean sectoral report, we will describe alternatives that improve productive, economic, environmental or social outcomes. Firm-level *productive* improvements are considered because some of the main problems of the dominant regime are associated to productive restrictions, and these are fostering the development of alternative pathways. And at the same time, some of these alternatives oriented at reducing productive problems produce important improvements in the outcomes we are interested in (environmental, social, and economic). The *economic* problems we studied are related to the long term dependence of the Chilean economy on copper exports, and the need for developing technological capabilities.

7.1 Productive

One of the main motivations for the existence of these research projects –and likely the one that helps it obtain funding from Codelco– is the need to increase the speed of copper extraction from underground mines, while being as certain as possible that no rock bursts will occur.

The work between the CMM's Geomechanics Lab and Codelco-Teniente's Rock Mechanics group provides one more tool in the set used by engineers that plan extraction, and helps them confirm or suspect of their ideas about how to proceed. In this respect, the results from the project can be seen as supporting decision making in a key area, and although it is extremely difficult to know if on the margin, the research has helped them avoid rock bursts, it is a fact that *"one rock burst that we avoid finances ten years of research"*.

The group has also worked on hydraulic fracturing (fracturing the rock by introducing a pressurized fluid), a concept used in the oil industry that could be key to the future of underground copper mining. Hydraulic fracturing is also related to rock bursting and the way in which the rock reacts to the underground mining process. It is also a technique that Codelco plans to use massively to prepare the rocks before the actual mining, as it "softens" the rock and in this way should reduce the probability of bursting.

7.2 Economic

The main economic problem associated to copper mining is the fact that the country is extremely dependant on copper, and it has not used the experience and possibilities associated to its extraction as a way to generate innovative products and services. There is also little R&D and collaboration in the industry, by international standards.

The collaboration between the CMM and Codelco described in this report shows that there can be exceptions to the above. It is possible to have rich and purposeful collaboration between mining companies and universities that produces world-class results. It is possible to produce frontier knowledge in Chile, close to basic science but at the same time applied in the industry.

The knowledge generated by this collaboration could be further codified and sold. While it is not immediately transferable to other sectors (neither in its codified nor its tacit forms), the capabilities developed in researchers associated to these projects could spill over to other industries, as they have been trained as highly competent researchers, that can at the same time understand industrial problems and work with firms. The specific knowledge developed in quite industry-specific, but not the capabilities and tools acquired. There have been some weak attempts in this direction, but nothing concrete has emerged yet.

Collaborations like this one can also have demonstration effects both on the side of researchers and firms, and promote the development of other similar ventures. There is also

important potential to generate international R&D linkages, although it is not sure if this particular case will also help induce domestic linkages.

7.3 Environmental

There are no improvements in this area associated directly to the case under study.

However, other CMM research groups have worked on environmental problems. And as described in the previous section, the capabilities developed by the researchers that have worked with Codelco-Teniente could eventually be used on environmental issues.

7.4 Social

In general, mining and other industries do not have the operation margins that they had before, there is strong pressure from society and local communities on every aspect of industrial operations that can cause social distress – a landscape development. One of them is job safety.

The improved understanding of the rock bursting phenomenon has a direct impact on reducing the probability of accidents.

Even if it risks going a bit too far, reducing the probabilities of paralyzing the mining operation has an important indirect social effect: it increases fiscal revenue, that in Chile is spent in a relatively efficient way and has important positive social impacts. The mine could even be closed if there was a large accident, and this would have a strong social impact through the loss of jobs. Moreover, besides decreasing ore grades, surface mining is also losing ground because of the difficulty in obtaining social approval for projects in some areas, and this makes underground mining capabilities even more important to maintain production levels.

8. Q4: In which ways has the availability of internet and/or other ICT technologies contributed to the development of the alternative?

The internet and communication technologies have not played a key role in the development of the alternative. As the CMM and Teniente are relatively close (especially compared to other important mining operations far from Santiago), the groups meet very often face to face, and most important –in terms of knowledge generation– communication occurs in this way.

On the other hand, computers, through specific software applications and the possibility of programming ad-hoc solutions and interfaces to use the results obtained in research, are absolutely fundamental for the work this research group has been conducting. They had made

it possible to work on complicated mathematic problems, to generate 3D visualizations of rock models, and to produce friendly graphical interfaces for the users.

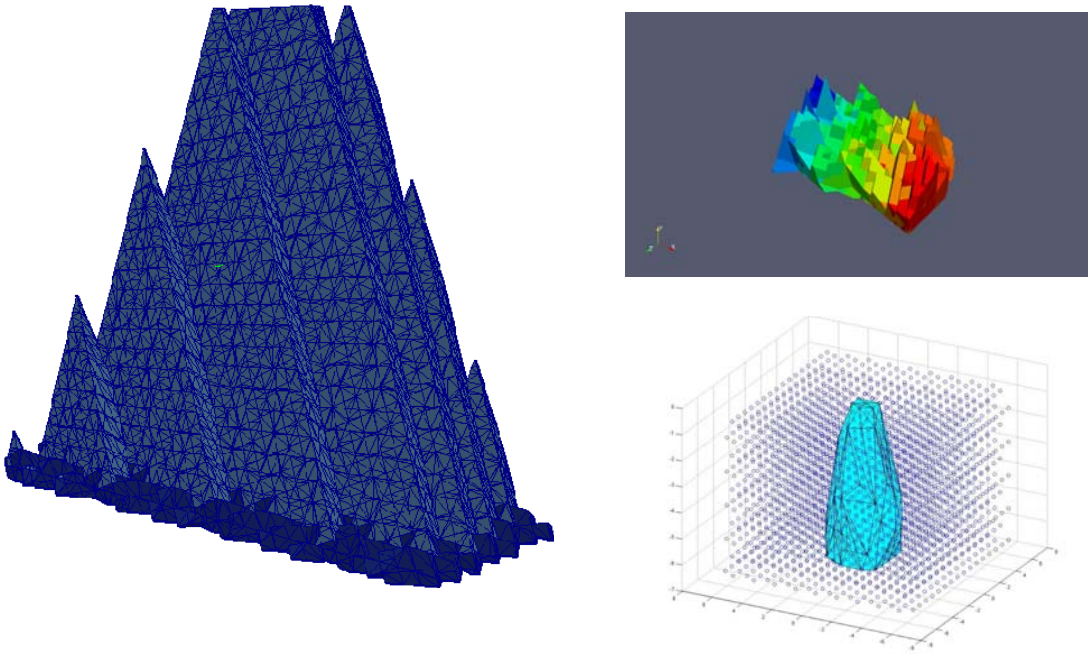

Figure 2 – Some examples of visualizations produced for different research projects.

9. Q5: Which are the main barriers that block the diffusion of the alternative?

For the barriers that are manifest in this case, we will comment on them in two levels: the specific case of the Geomechanics for Mining lab, and its relationship with the general concept of mining companies-university researchers collaboration. The reason for this is that we are interested in the diffusion of *this type of collaboration and research*. While we focus on particular cases to study how path-creating alternatives develop, the broader idea of path-creation is to develop dynamic comparative advantages starting from the experience in natural resources.

9.1 Capabilities

The Geomechanics group at the CMM has been able to find researchers and assistants to work on their projects, but they are at the limit of their possibilities. It seems like they would not be

able to grow much in size right now if the opportunity presented itself, besides not having time for diffusing the learning from their projects inside the university. Lack of qualified human capital could be an important constraint for the group. Related to this, a significant part of the work has been conducted by students, who usually stay for a relatively short period of time. This makes it more difficult to have long term plans. Thinking on other potential similar cases, there is in general a lack of researchers that appreciate applied work and who have experience conducting it. This could difficult the training of other applied scientists.

Something that was considered key by all actors involved is that fact that there was a mathematician at Codelco. This made it possible for both sides to interact. In general, the Codelco team is highly qualified, and this has made possible a productive collaboration with the mathematicians. But this is an exception in terms of the national economy. Other large mining companies that are also in the technological frontier can probably establish meaningful collaboration with advanced research groups. But in the rest of the economy –thinking in path-creation as diversification in general– it would probably be much more difficult to establish this kind of dialogue, as firms do not have the qualified individuals that are needed to interact with researchers.

9.2 Economics

The figure of *technological brokers* is a key missing link for many of the research projects that are developed in Chile.

In this particular case, it is very clear that Codelco is interested in improving the mining operations and *not* in commercializing whatever that resulted out of these efforts that could be sold. On the other hand, researchers are interested in doing research, and not in everything related to marketing products and giving support for commercial software. An intermediate between the company that funds research, the researchers, and the market for the results, is fundamental if the results from research are to be commercialized.

With respect to the stability of inbound money flows to maintain the team, being a part of the CMM has been important. In some cases, the CMM has been able to support the group, for example when payments have been delayed. Still, longer term funding and planning remains an issue.

9.3 Politics and power

A very serious problem in the Chilean economy is the little private interest (observed through the lack of resource commitment) in R&D. One possible explanation for this, especially in the natural-resource based sectors, is the fact that it is possible to obtain rents from resources without competition and without being forced (not by the market nor by the State) to invest in R&D (Palma, 2011). We can consider this to be a landscape problem, as it is located at the level of political economy, above any particular industrial sector.

Codelco in this case presents an exception to the above. Being a public company, it can have objectives besides profit seeking, even if these are not always formal or explicit. What has been heard throughout the fieldwork, and also observed in the quantitative paper, is that Codelco is interested in producing knowledge demand and help the country develop technological capabilities. There are also critics that say that this has not been as strong as it should, but it is important to remember that there are always the productive objectives, and it is against these that teams and individuals have their *"odious benchmarking comparisons"*.

9.4 Institutions

This particular case is about the collaboration between a public university and a public firm. As we found in the quantitative report, it is precisely these two organizations that are at the core of many R&D efforts in the mining sector. While their public nature might give them both the interest in promoting national development and wellbeing, it also poses particular problems. Public universities have administrative constraints that make it difficult to generate spin-offs. Codelco –or at least people associated to Codelco– might be interested in investing in R&D, but the fact that it is public money involved means that lower levels of risk can be tolerated.

The rules under which this successful collaboration has occurred, including the formal and informal institutions inside the mining company and the university, as well as the way the collaboration has occurred, are not common in the industry. In most cases, the way universities are organized is not helpful for working with the industry, and it is very hard to develop rich and productive relationships between academic and industrial counterparts, because, on both sides, the actors are not prepared for it. On the part of mining companies, a characteristic of this case is that the mining operation at Teniente has flexibility in their innovation strategy vis-à-vis the rest of the company. This could be a barrier in the rest of the sector, and this case could be showing an interesting exception.

9.5 Cultural

The Chilean society has low levels of trust, which are closely related to the low levels of collaborative work observed.

In this case, this is manifest through Codelco's opposition to the diffusion of findings (however this recently changed). Trust and collaboration also matter at the level of individuals and teams, in this case we can see that both teams have developed a positive research relationship with trust and collaboration, where they meet very often and openly discuss all important matters. As one interviewee stated, in these meetings things like *"that thing is totally useless"* can perfectly be said.

Another cultural problem associated to the research community is its general disregard for anything that is not academic. Again, this is *not* the case in this initiative. Researchers are not only happy to work on an applied problem, but just as important, they understand their hierarchical position in the solution of the problem. It is the mine that "owns" the problem, together with most of the understanding about what could eventually work and what could

not. The researchers understand and assume these, and their work is oriented at providing tools to support the engineer's work.

Rather than a limiting factor for this case, we are using the as a remarkable counterexample to two common problems that could block the development of other path-creating alternatives.

10. Summary

In this report, we covered our main research questions for the case study of the Laboratory of Geomechanics for Mining, located at the Center for Mathematical Modeling. The research group has been working for about a decade with the Rock Mechanics group at Codelco División Teniente, chiefly on the problem of rock bursting, one of the most serious threats in underground mining. Being interested in its development as a path-creating alternative, we focused primarily on describing this particular research relationship, but we also relate our findings to what is happening or could happen in the country in terms of diversification in general.

When looking at the scope of the alternative, we see it is mainly an isolated initiative between the two groups, but that has started being more open at least to the research community. At the same time, its prospects are significant, as underground mining is the future of large scale copper mining. It is also important to think on the researchers that have been trained under this group, that will have the tools to do applied research, not common in most academic areas. They have acquired tools and abilities that could be important in other economic sectors, although this possibility remains hypothetical for the most part. Learning has been significant, but up to now, limited to the two collaborating groups.

With respect to the distance to the dominant trajectory, this cannot be defined as a comparable scalar for most dimensions, especially because of the path-creating nature of the case under study. But we can find similarities and differences. For example under the guiding principles, safety plays here a fundamental role, although increasing production is still the ultimate objective. The "products" produced by the alternative are mostly knowledge-related: knowledge about the problem (that could be codified and sold), trained professionals, and experience about successful collaboration. When thinking about technology, what could be more interesting to compare between the alternative and the regime are the "social technologies", specifically the institutions behind the productive collaborative relationship that was established. A relevant difference in organizational structure is that research here is located at a particular mining operation, and a specific team, in contrast with innovation and research policy usually located at the companies' headquarters. Again a difference with the regime is the cognitive distance between engineers and researchers, that was bridged both thanks to the disposition at both sides and to the existence of a mathematician among Teniente's engineers. Culture and values are strongly related to the guiding principles, and besides the interest in safety, it is remarkable that Codelco is a public company that can target promoting diversification as an objective, even if this might not be official or lead from the

corporate level. The openness of researchers towards applied work is also a remarkable difference from the dominant attitude in academia.

The promises for improved outcomes are mainly two: reducing rock bursts (saving lives and avoiding halts in production), and promoting other path-creating, knowledge intensive activities that could produce innovation-driven economic growth. The former are difficult to verify empirically, but as was stated in Codelco, one accident avoided would pay for many years of research. Moreover, the group's work could be extremely important for Codelco's long term production levels. The diversification-related outcomes are a clear possibility, as the profile of researchers that have worked at the group is ideal for establishing consultant companies and develop applied research. However, we still have to see whether this will ever materialize, something that is related to the local entrepreneurship culture and private sector demand for R&D. The development of marketable products from the work produced by the research group is another very real possibility, but it seems to rest on the existence of technological brokering.

Regarding ICTs, communication technologies or the internet have not been relevant except for coordinating meetings (most communication is face to face). On the other hand, powerful computers and software tools have been key for the group's work. Computers are used to work on complex mathematical problems, and specialized software packages are used in some of the projects' outputs. And most of the final software tools delivered, that include graphical interfaces and the underlying programs based on the results from the research, are ad-hoc programs made by the Geomechanics Lab team.

When we look at barriers to the alternative's diffusion, we find that the research group might be constrained in its human resource availability, and relies excessively on students that usually stay for relatively short time periods. Another problem is that Codelco and Universidad de Chile have particular bureaucratic problems due to their public nature. The lack of technological brokers to commercialize software tools made by the group is another important missing link in the innovation development chain. On the positive side, we see this case as an example of several exceptions to some serious and very common problems that affect path-creation in the Chilean economy. Codelco might provide important knowledge demand when it does not come from the private sector, something that could be related to the fact that rents can be obtained with relative ease and R&D is not necessary. There are also some cultural problems that limit innovation in Chile: lack of trust, lack of experience and desire to collaborate (closely related to the former), and a disregard for productive activities by researchers. In this case, those three are reverted, and result in the generation of a long term relationship that produces world-class knowledge on the technological frontier.

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