Opening up Natural Resource-Based Industries for Innovation: exploring new pathways for development in Latin America
Quantitative Report: Copper Mining in Chile

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1 Introduction

This project on technological trajectories has two components of study in each country: a qualitative case study, and a quantitative study using innovation funds data. In the case of Chile, where we are looking at copper mining, the particular cases studied in depth are not strongly associated to public funds, and the majority of them are not inserted into or forming an important network. So we decided to use the innovation funds data to have a more general overview of the evolution and direction of public-funded research in the mining sector, and whether it is promoting or not the development along more sustainable trajectories. In this way, this study acts as a complement to the case studies, increasing the breadth of the analysis, at the expense of depth. Still, the data used is far from being representative of all projects occurring in the sector, as we will explain below.

Out of the different innovation funds databases available[1], we decided to work with FONDEF projects, for several reasons. The program is one of the largest in terms of number of projects funded. It has been active for over 15 years, funding over a thousand projects. FONDEF projects are associative, and there is detailed data about participants in each projects, making it possible to build collaboration networks, that form the core of our analysis. Another positive characteristic is that FONDEF is oriented to applied research, funding projects that do have a component of more basic research, but that at the same time should not be too far from industrial application. However, this is at the same time a disadvantage, as we do not have data on basic science or on applied innovation projects[2]. And we have absolutely no information about all projects that are developed without public funding, with mining companies' funding. These caveats must be considered when interpreting our results. Nevertheless, we did find some strong and very interesting patterns in the data.

In terms of the transitions framework, we can consider FONDEF-funded projects to be protected niches, because of the secured funding they have, and the support from both a firm and a research center. We studied the networks of projects along the dominant trajectory and those that represent alternatives pathways for copper mining in Chile, and tried to obtain as much information as possible from the data available.

In section 2 we will describe the methodology used. Then, in the third section, we will characterize the projects in different dimensions. The fourth sections presents the networks formed by the different keywords used in the projects' descriptions, focusing on the different types of problems (economic, productive, environmental and social) described in the sectoral report. The fifth section presents the core of the analysis, i.e. the collaboration networks formed through joint participation in FONDEF projects. The final section presents some conclusions and links between this report's results and those of the qualitative study.

2 Methodology

Once the database to work on was decided, we proceeded to filter the FONDEF database to keep only those projects related to copper mining. We did this in three ways:

- Projects with important mining keywords (mining, copper, minerals, etc.) were kept, no matter their discipline
- Projects in mining-related disciplines (metallurgy, mining engineering, etc.) were kept, no matter their names or descriptions

[1]Most of public funding for innovation in Chile occurs through CONICYT (the agency in charge of the promotion of research and scientific development), or CORFO (that funds firm-level innovation projects). Each agency has a series of funding lines, most of them neutral in terms of economic sectors. CONICYT's funding is closer to basic scientific research, with funding lines such as FONDECYT or FONDAP. CORFO in turn, through its InnovaChile branch, support firm-level innovation with different types of subsidies, depending on the firm's needs (seed capital, prototyping, technology transfer, etc.). FONDEF is a CONICYT funding line that is somehow in between science and firms, as it asks them to collaborate to fund pre-competitive research.

[2]FONDEF is one of the few funding lines that has network data, there was no possibility of performing a network analysis for other funding lines.

Type of problem	Specific problem
Environmental	Air pollution
	Water pollution
	Soil pollution
	Fresh water availability
	Residuals
	Other environmental problems
Social	More or better employment
	Quality of life
	Job safety
	Other social problems
Productive	Low ore grades
	Energy availability
	Fresh water availability[3]
Economic	Development of suppliers (in general)
	More connections across economic actors
	Knowledge intensive suppliers
	Lack of research

Table 1: **Problem categories**

- After those two filters, projects that were later found to be unrelated to copper mining were dropped

Each type of problem (economic, productive, environmental and social) was divided into sub-problems, as described in the sectoral report (details in Table 1). For each sub-problem, a broad list of keywords was built. The keywords were indented to identify projects that tackle those problems in alternative ways.

A script was programmed to help analyze the data. The script scanned the project's name and summary, looking for the different keywords, and then presented a list of projects for each sub-category. For each project, it highlighted the keywords found, and allowed the researcher to confirm whether the project was effectively an "alternative" project related to that problem, an alternative associated to another problem category, or simply a project in the dominant sociotechnical trajectory. The script made it possible to perform a thorough and relatively quick review of the projects; it was not feasible to go through all of the project summaries thinking at the same time about all possible sub-categories of problems. Finally, the script presented a list of all projects that had not been classified in any category, to review them manually.

Projects could be classified in several categories at the same time (e.g. "knowledge intensive suppliers" and "air pollution"). Moreover, there are projects that were classified as dominant and alternative at the same time. The reason is that while these projects did have important positive outcomes in some of our categories of problems, the projects were for the most part in the direction of the dominant regime.

After classifying projects, different networks and statistics were generated, these will be discussed in the following sections.

3 Characterization

Before the networks of keywords and projects, a general characterization of the projects and their classification is presented. Two databases were used. First, a database with details about all FONDEF projects awarded between 1991 and 2007, a total of 1129 projects. The second database was obtained using the law of access to public information, and includes data on awarded and rejected FONDEF

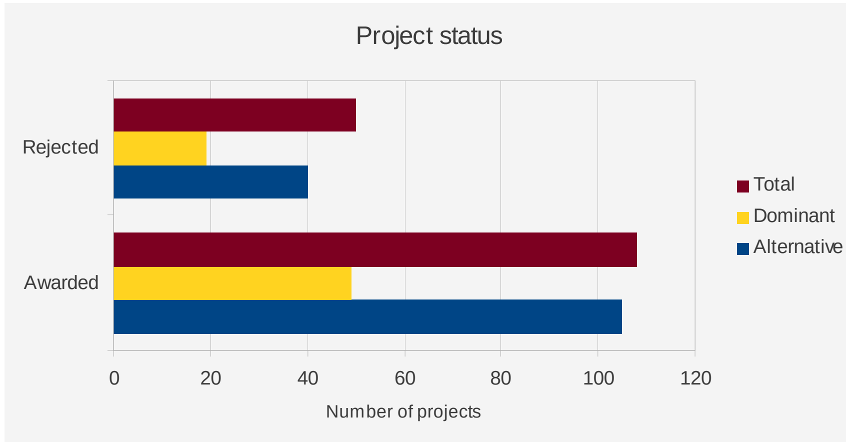

Figure 1: **Awarded and rejected projects**

applications[4]. This database had a total of 3952 records. After filtering the projects, 142 remained from the initial database, and 103 of the additional one (after deleting duplicated ones). This total of 245 projects were reviewed with the helper script. Out of the 245, 183 were finally classified into at least one of the categories, and for different reasons the rest were discarded.

Because the additional database that includes rejected projects does not include complete network information, these projects had to be dropped for the network analysis. The characterization in this section includes all of the projects analyzed, to have a more complete view over the universe of FONDEF projects and its distribution across dominant and alternative paths. On the other hand, information concerning accepted and rejected projects uses only projects from the second database.

Before presenting more details, it must be remembered that projects could be classified simultaneously in several alternative categories, as well as being alternative -in some dimension- and dominant -in spirit.

First of all we compare awarded and rejected projects, and observe that the percentage of rejections is strikingly similar for projects classified as alternative (72,4%) and for those classified as dominant (72,0%), suggesting there is no bias favoring projects in the dominant trajectory.

Then we look at projects by year and by region. Looking at yearly data[5], we find a worrying pattern: FONDEF projects associated to copper mining have been decreasing. And the decrease has been similar both in dominant and alternative projects. At least 2009 seems like a change in this decreasing trend, that could be associated to policies to encourage R&D and innovation in the copper mining sector. The evolution of these projects in time, and their relationship with overall FONDEF funding will be discussed later, when networks in different time periods are considered in section 5.2.

The regional distribution of projects does not shed much information. As expected, most of the projects are administratively based in Santiago, probably because of the leading institutions being universities located in the capital. The Concepción Region (VIII) has a much higher share of dominant projects than the rest of the country, probably because the leading university in that region is recognized as one of the best in the country in metallurgy.

3.1 Alternative and exclusively alternative projects

As projects can be classified as dominant and alternative at the same time, we want to see if there are differences across projects that classify as both and those that are "exclusively alternative", meaning they tackle one of the identified problems and do this moving away from the dominant regime.

[4]This database contains projects up to the year 2011, but we are not certain about the completeness of the database.
[5]No FONDEF projects were awarded in the 1993-1995 period

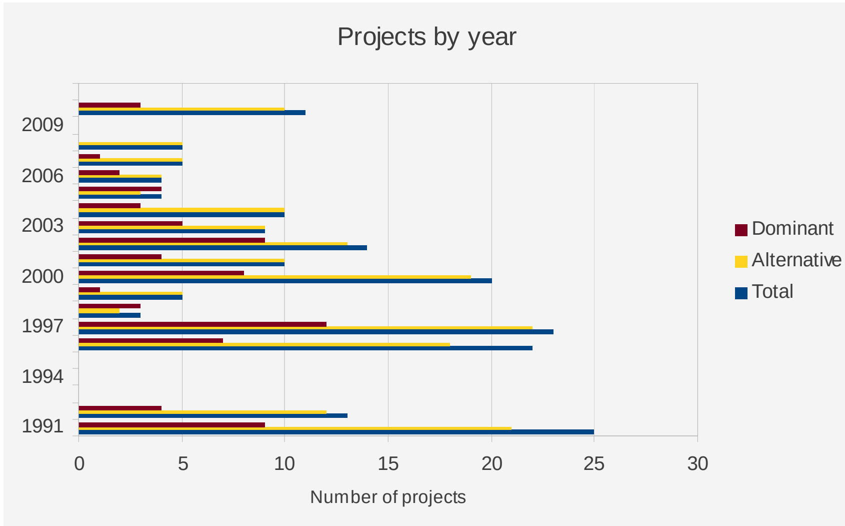

Figure 2: **Projects by year**

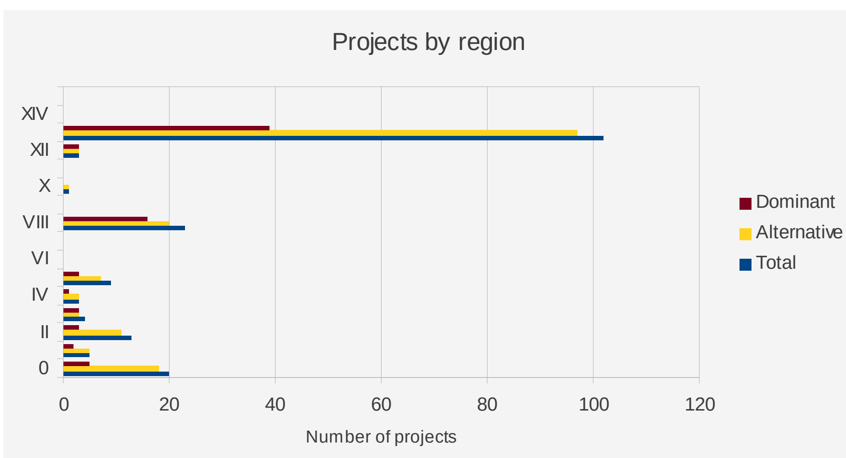

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Figure 3: **Projects by region**

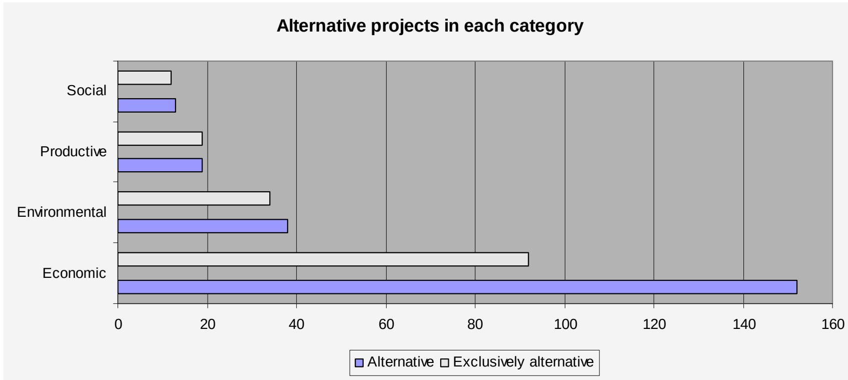

Figure 4: **Alternative and exclusively alternative projects by category**

Roughly, we can associate this distinction to our classification of "path-repairing" and "path-breaking" alternatives, although when looking in more detail most of the projects fall into the "path-repairing" category, although with different degrees of divergence from the dominant regime.

The graphics in this section are built from a total of 157 projects that were classified into at least one alternative category.

First of all, we can see that for Social, Productive, and Environmental "alternative" projects, the large majority of them are "exclusively" alternative, meaning projects in these categories are focused on solving the problem at hand. On the other hand, only 60% of problems classified as tackling economic problems are exclusively alternative. This means that many projects that can be seen as improving economic outcomes, do so while still moving along the dominant sociotechnical trajectory.

We can then look at subcategories, to see whether there is a difference in the propensity to be exclusively alternative across different types of problems.

First we look at the absolute number of projects, and see that economic alternatives are largely dominated by "knowledge intensive suppliers". This helps explain why many economic alternative projects are in the dominant trajectory: while they are developing knowledge intensive suppliers that could be important for the development and accumulation of technological capabilities, they do so while improving the dominant technological trajectory. Looking at the other categories, we can see that many environmental alternatives do not fall into our classification, something that can have a positive interpretation; there is research being conducted to improve environmental outcomes in many different dimensions. Productive alternatives focus more on the problem of low ore grades than in energy availability, and social alternative problems are dominated by job safety related projects.

Then we look at the percentage of alternatives projects that are exclusively alternative under each sub-category, and do not found much heterogeneity. It is interesting to see that biotechnology projects are for the most part exclusively alternative, i.e. this new technology is not only generating domestic capabilities, but also helping steer the sector away from the regime's problems. It is also good to see that all productive alternatives are exclusively alternative, this means the sector seems to be looking elsewhere for tackling some of its major issues. On the other hand, it is not good to see that there are no exclusively alternative projects related to fresh water availability. Consistently with our qualitative study, it is possible that most of the initiatives in this direction are done with only private funding.

3.2 Evolution in time by category

Decomposing the evolution in time by category we see that the most pronounced fall has been in Economic alternatives, but the fall in the other categories, most notably social, is even more dramatic, because it means going as low as no projects at all[6]. The coefficient of variation normalizes volatility

[6]It should be remembered that during 1993-1995 no FONDEF projects were awarded at all.

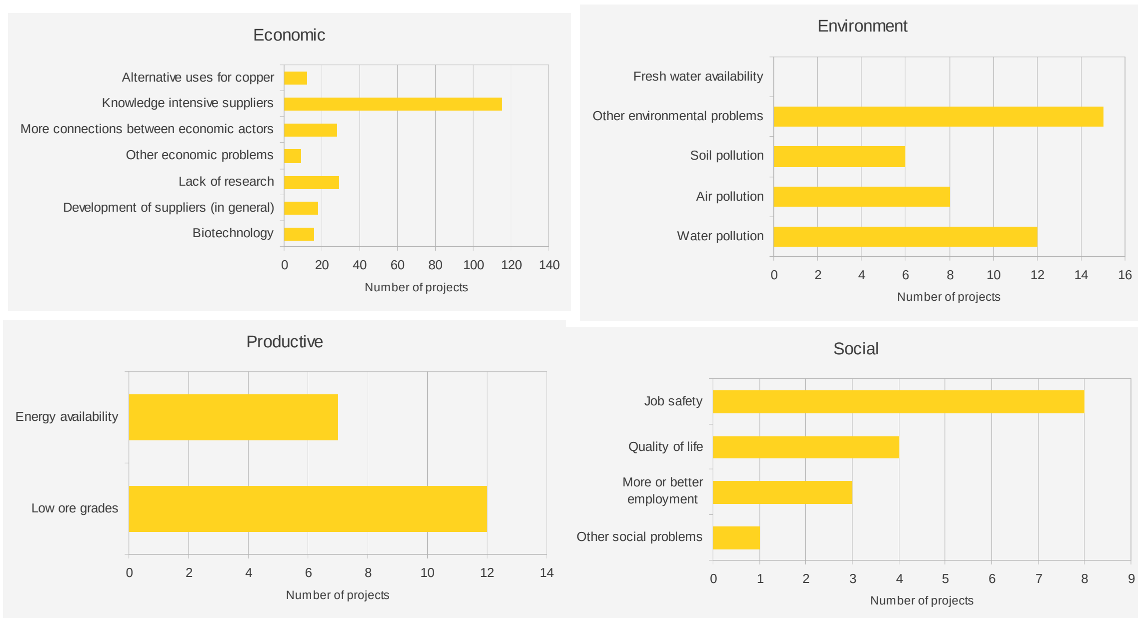

Figure 5: **Number of alternative projects in each sub-category**

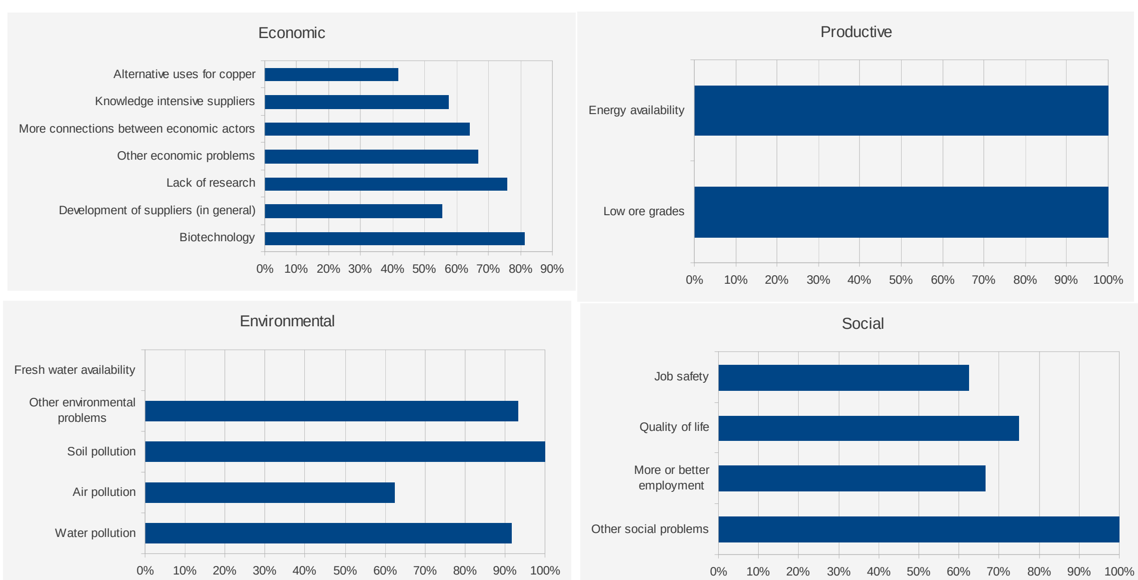

Figure 6: **Percentage of exclusively alternative projects in each sub-category**

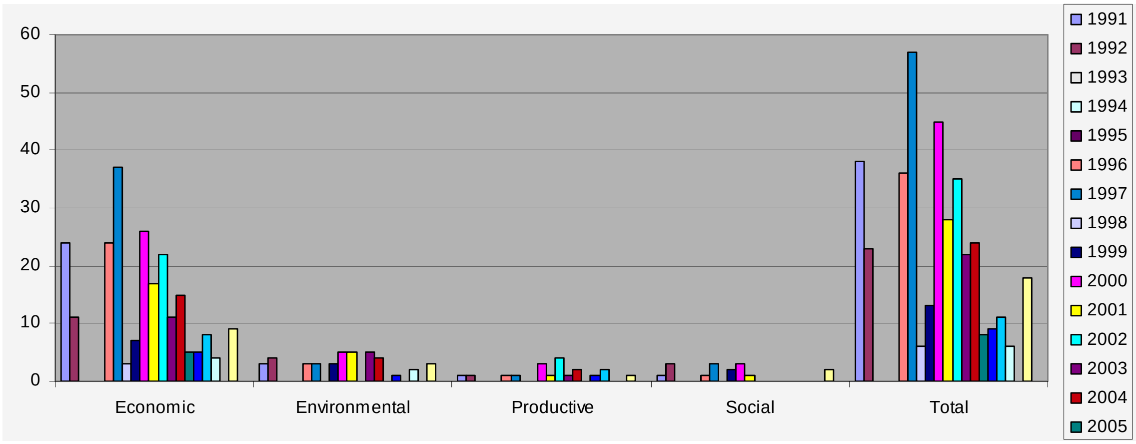

Figure 7: **Projects by year for each category**

	Mean	Median	Std.dev.	Coefficient of variation
Economic	10.86	8.00	10.56	0.97
Environmental	1.95	2.00	1.96	1.00
Productive	0.90	1.00	1.09	1.21
Social	0.76	0.00	1.14	1.49
Total	18.05	13.00	16.74	0.93

Table 2: **Descriptive statistics for yearly number of projects**

by mean size, and shows that economic projects have actually less volatility than the other categories. In short, there is no stable development of alternative FONDEF projects in the different categories. The negative interpretation is that research is not increasing, the positive one that research has moved away from FONDEF towards firm-innovation funding lines and private funding. Data to check this is not easily available, but our impression is that we can be moderately optimistic about this.

The evolution in time by subcategory does not shed much information. There are only two clear trends. One is in water pollution projects, that increased from 1997 to 2004 but then started decreasing, and the other in knowledge intensive suppliers, whose projects have been falling. Again, nothing can be said with certainty without looking in detail at projects funded with other public instrument or private funds.

Results for the evolution of acceptances and rejections in time for both alternative and dominant projects are not reported. There is no clear tendency, the percentage of approved projects every year has significant volatility both for dominant and alternatives projects, although with a slightly increasing trend for both.

3.3 FONDEF categories

One of the data fields available for each FONDEF record is its classification under "FONDEF categories". Although there are some doubts about the quality of the information registered under this field, we show below a network where the different categories are connected when they are shared by at least one of the projects. The size of the nodes represents the number of connections each node has to other nodes, and the width of the connections represent the number of links between each particular pair of nodes. The original categories names in Spanish are displayed.

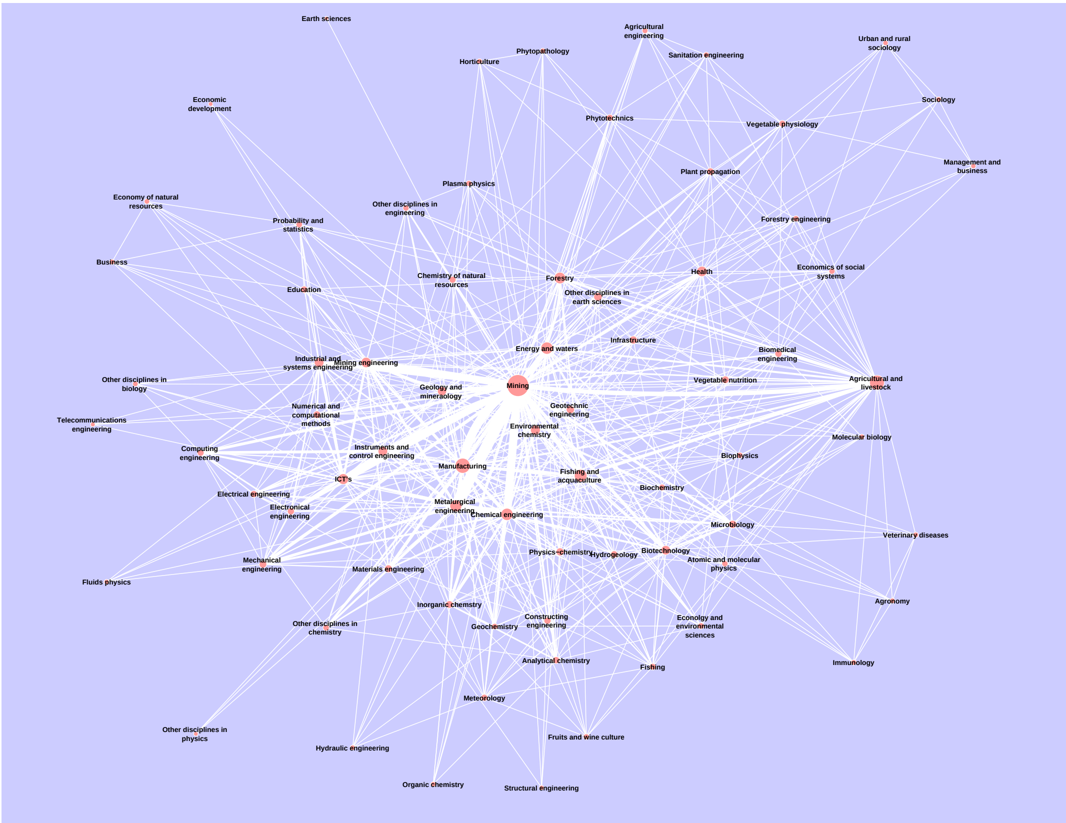

Figure 8: **FONDEF categories network**

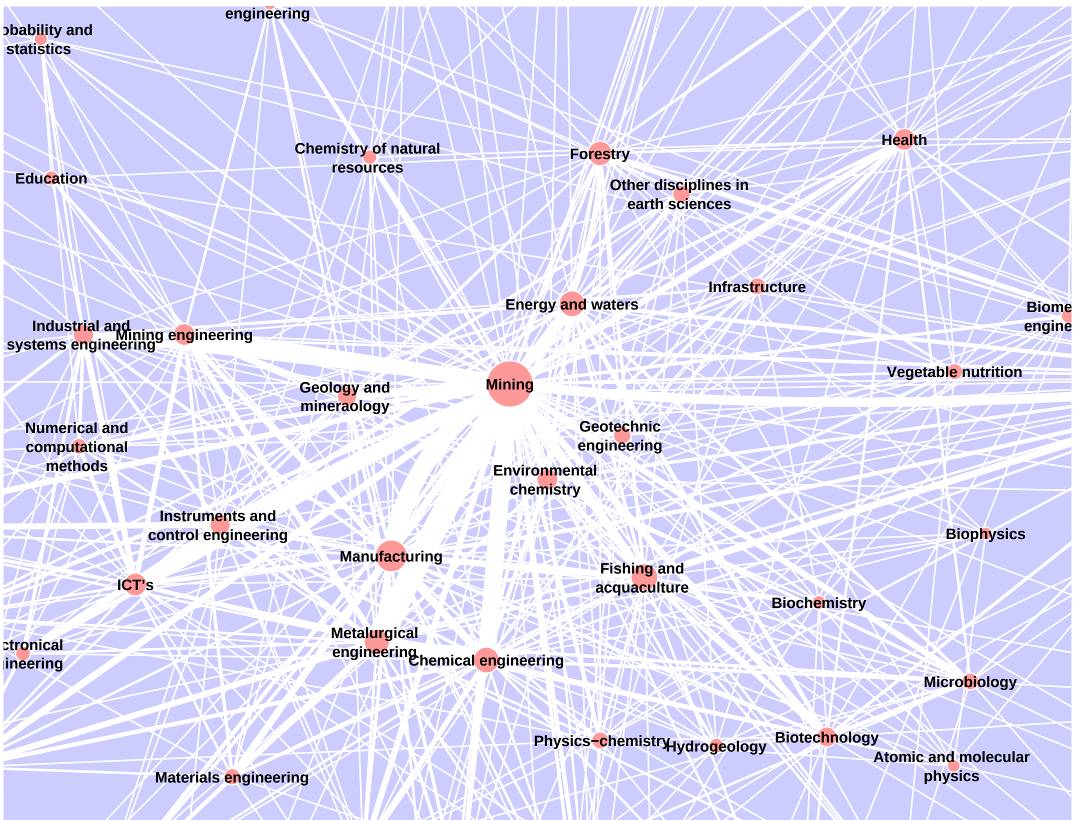

Figure 9: **FONDEF categories network (zoomed in)**

The diagrams above show the FONDEF categories network for alternative projects. The core of the network is clearly associated to areas such as mining, geology, chemistry, and engineering. On the edges, however, all kinds of disciplines appear. At first it is not clear whether the classification into this categories has not been very rigorous, or whether the alternative projects are close to many different types of scientific disciplines. Some categories that seem interesting, such as telecommunication engineering appear very weakly and badly connected. What is reassuring is that the network of dominant categories (now shown) has only 48 disciplines, while the alternative one has 75.

4 Keywords' networks

To have a general impression about what kind of "alternative" projects are under development, this section presents networks of the keywords used in the projects classified under each category. Two keywords are linked if they show up in the same project.

As above, node size represents the number of connections to other nodes (its "*degree*" in network theory terminology), and the width of the connections or "*edges*" represents the number of times that particular connection is repeated in different projects.

These networks are obviously restricted by the keyword list itself (but it should be remembered that final classification was manual, not automatic), and as they are not the center of our analysis, only a preliminary, relatively unpolished version of the networks is presented[7].

The diagrams presented in this section contain the original keywords in Spanish, and only the more interesting diagrams are shown.

A final caveat is that some networks are based in a fairly small amount of projects, no strong conclusions should be made out of the smaller networks.

4.1 Economic problems

First of all we present the network of keywords of all Economic problems-related alternatives (under our terminology, these are mostly associated to "path-creating" alternatives). It is good to see that engineering, optimization, services and regional are important keywords (beyond the expectable ones such as technology and knowledge). However, other that should be important, like innovation, cluster, or collaboration, have only a marginal position.

The network for knowledge intensive suppliers show an important role for knowledge, engineering, technology, modeling and research, as expected. It is interesting to see that biotechnology and automation seem to play an important role.

4.2 Productive problems

The network for productive problems shows a clear predominance of energy-related projects, possibly caused by a better keyword selection for this subcategory. At least there is a clear pattern in this category, projects relate to the demand for electricity, and try to solve the problem by using alternatives to fossil fuels.

[7]In particular, some keywords that refer to the same concept should be merged. Doing this would only reinforce some of the patterns that can be already observed.

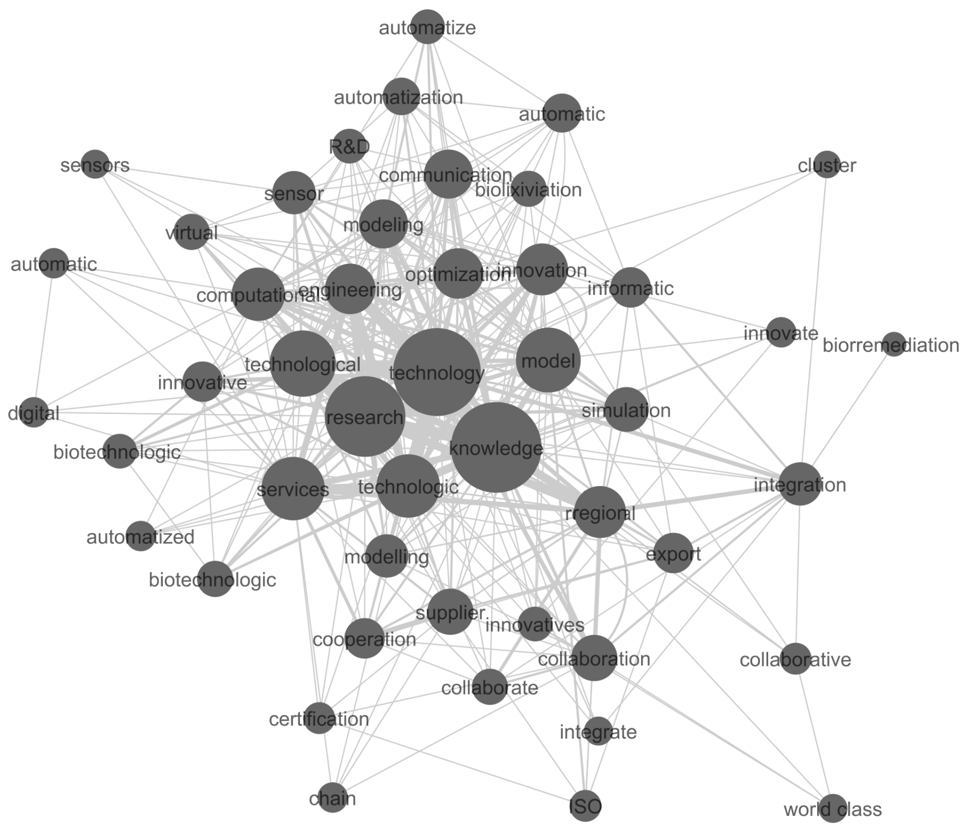

Figure 10: **Economic problems keyword network**

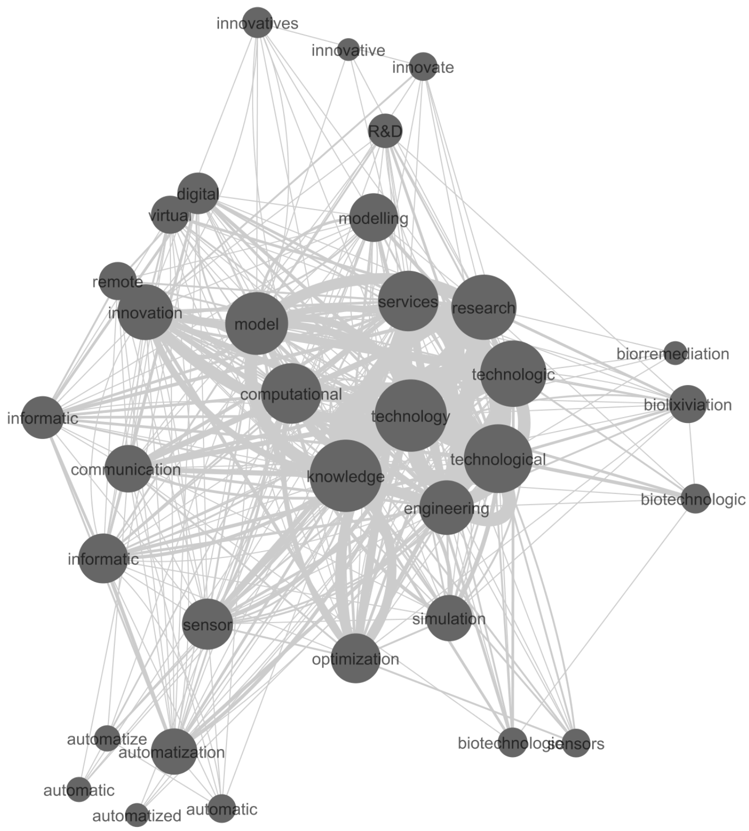

Figure 11: **Knowledge intensive suppliers keyword network**

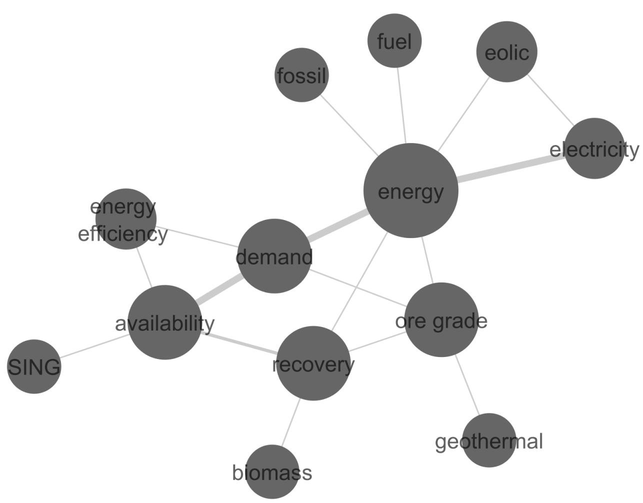

Figure 12: **Productive problems keyword network**

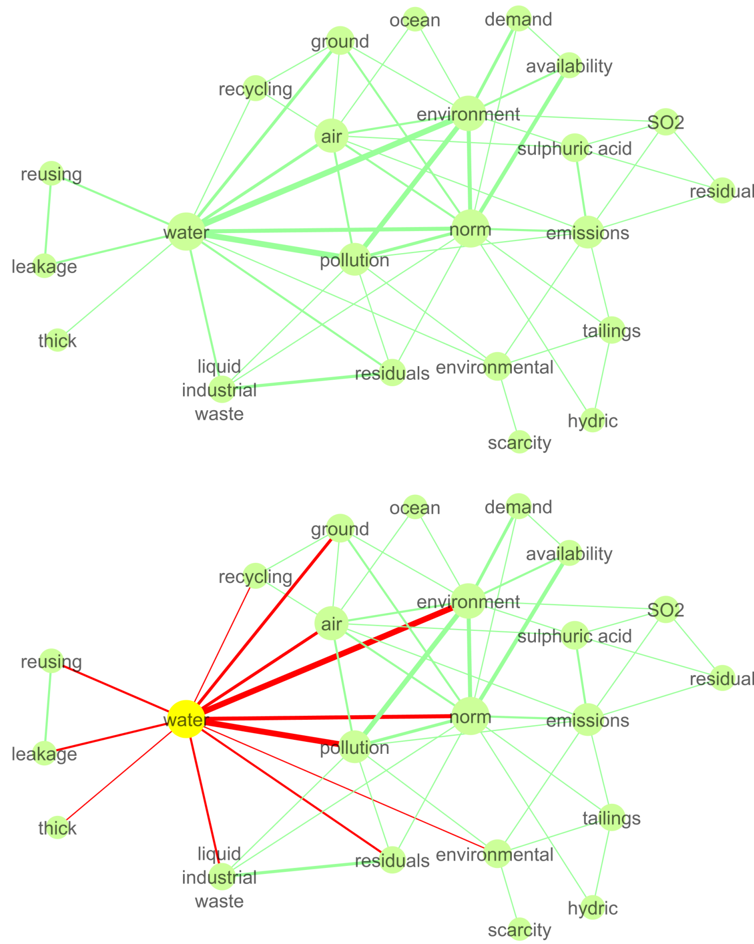

Figure 13: **Environmental problems keyword network**

4.3 Environmental problems

The keyword network for environmental problems has several interesting characteristic. First of all, "norms" have a central role, suggesting that there is need for and/or interest in doing research related to norms and regulations. Water has a very central role. As can be seen in the lower graphic, the node's connection stretch toward a significant portion of the network.

The core of the network is formed by norms, water, and pollution, however none of them seem to clearly dominate over the other. A significant missing concept is desalinization, or anything related to the use of salted water in the production process. This is consistent however with the fact that the use of sea water in the process has been spearheaded by only one mining group at a large scale.

The diagrams for soil and water pollution highlight the idea of leaking and underground pollution.

Again there is a significant missing concept in the soil pollution network: thickened tailings. It only appears weakly and marginally.

4.4 Social problems

The network of social alternatives has a core formed by safety, health, community and employment. What strikes as having such a small and unconnected role are the concepts of social responsibility

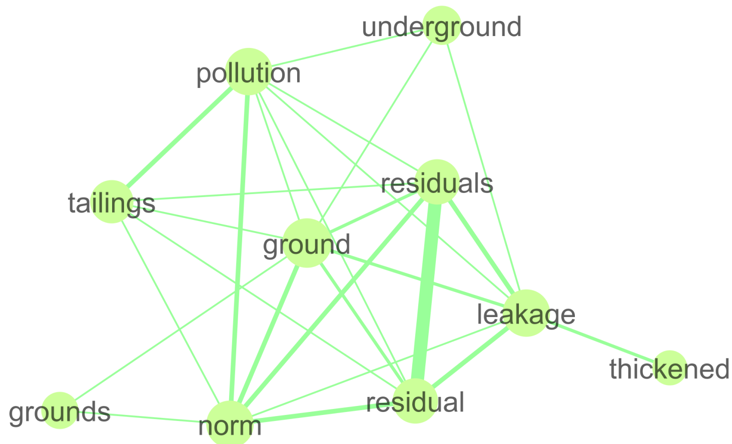

Figure 14: **Soil pollution keyword network**

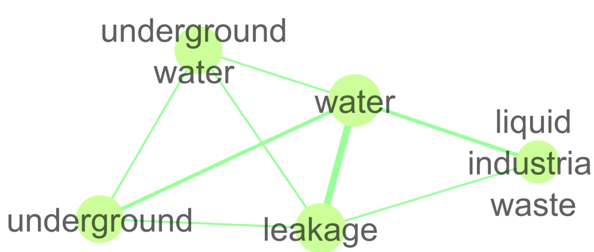

Figure 15: **Water pollution keyword network**

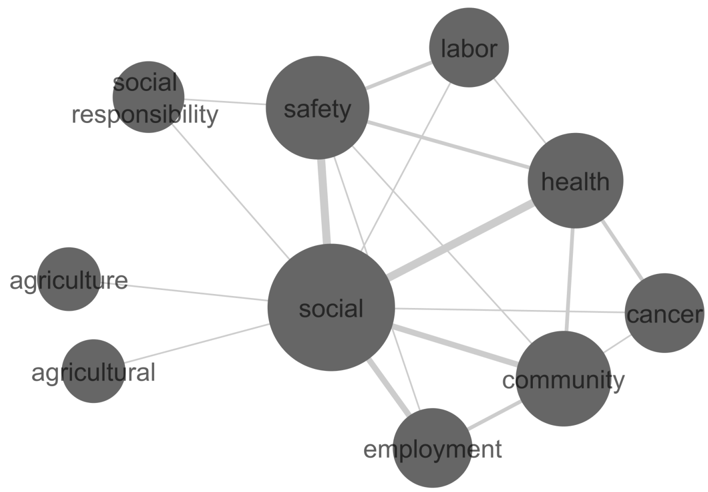

Figure 16: **Social problems keyword network**

and agriculture. The former has been a flag much waived by mining companies, but maybe more for marketing purposes than anything else. The latter is a sector of critical social relevance, that has had many problems with the mining sector, but at least not much is being done through FONDEF projects in this respect.

4.5 Complete keyword network

Finally, Figure 17 shows a network of all the keywords and problem categories put together.

It is shocking that collaboration does not show up much. More positive are the prominence of the concepts norms, social, and region, which were unexpected.

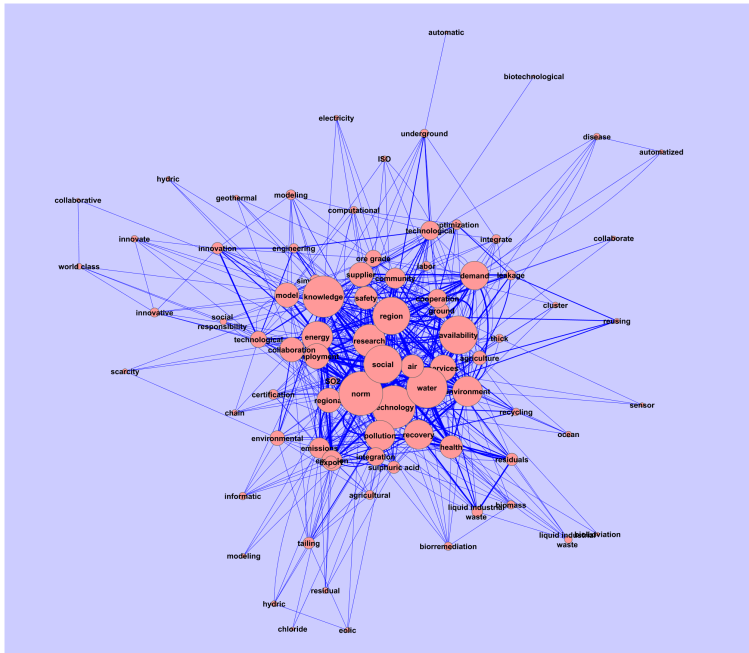

Figure 17: **Keyword network**

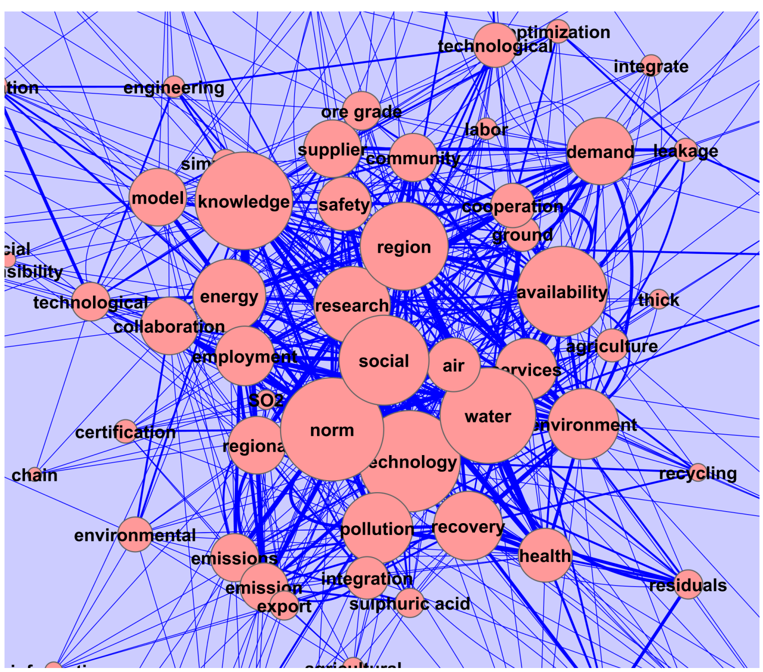

Figure 18: **Keyword network (zoomed in)**

5 Collaboration networks

This section includes the main networks of interest, collaboration networks of FONDEF projects in copper mining[8]. First we present some diagrams that summarize how collaboration occurs across different types of actors. Sections 5.2, 5.3 and 5.4 present the evolution of collaboration networks in time, the network of projects along the dominant trajectory, and networks for different problem categories respectively.

Across the whole section, some graphs are presented simulating how the network would have been like without the participation of Universidad de Chile. The reason for this is that our preliminary analysis, together with our knowledge about the public instrument and the mining sector, showed that Universities have the incentives to initiate these projects and look for partners to collaborate with. Among universities, Universidad de Chile tends to participate in a large amount of projects, have strong collaboration links with other organizations, and have central positions in most of the networks. As a simple experiment, we simulated how the network would look like removing this university from different networks of interest. What we do is to assume that Universidad de Chile lead the projects where it participates, so we completely removed the whole projects where it participated, rather than simply removing the node. Doing this could have structural impacts in the network, both because a central actor is removed, and because other actors and connections across actors can also disappear from the network. We want to see whether collaboration networks and their characteristics are robust or not to the removal of this central actor.

As in the previous section, some networks are based on a small amount of projects, so conclusions obtained from them should be cautious.

5.1 Overview

All organizations that participate in mining FONDEF projects were classified in the following categories: associations (business associations and similar organizations), universities (includes also research institutes), mining companies, government agencies of different types, and "others". Most of the "others" are suppliers of mining companies.

Figure 19 shows an overview of how collaboration occurs between different types of institutions and across institutions of the same type. The figure on the left corresponds to alternative projects. Universities appear as the main actor, within a large -and equal- number of connections to "others" and mining companies. The government plays a relatively minor role, and collaborate in similar amount with universities, others, and mining companies, although the latter are the ones with the highest amount of connections to the government. Associations, in contrast with what was expected, play only a marginal role in FONDEF networks. With respect to inter-group collaboration, it is highest (in absolute terms) for "others", then for universities, and then for mining companies. It is interesting to note that while they have about the same number of connections with other types of organizations, "others" collaborate among themselves a 40% more than mining companies do. In other words, suppliers seem to be more interested in collaborating with equals than mining companies.

The figure on the right shows the same diagram for projects classified as belonging to the dominant trajectory. Universities are still the central player, but this time they have significantly more collaboration with mining companies than with "others". One explanation could be that suppliers are relatively more involved in alternative projects than mining companies. This is consistent with the fieldwork evidence, mining companies avoid distracting themselves away from their core business: digging minerals. On the other hands, developing alternatives is key for new, technologically intense suppliers: they are creating new demand from mining companies. In the case of alternatives, suppliers might need to have deeper involvement in the development projects, as new ways of doing things are being developed. In dominant projects in contrast, suppliers might simply act as suppliers.

Consistent with the above, mining companies collaborate proportionally less with "others" and more with universities in dominant vis-à-vis alternative projects. This could be looked at from another

[8]Only projects with several participants are considered for the construction of networks.

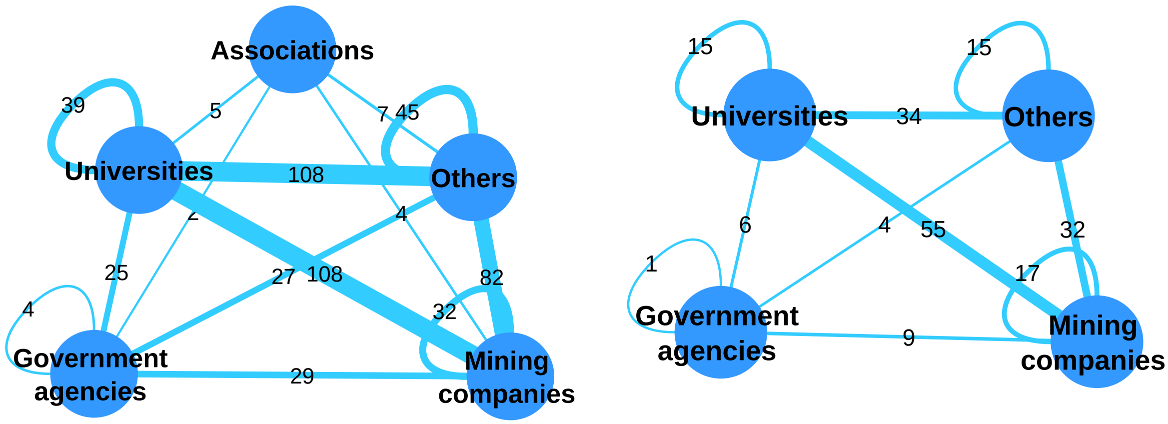

Figure 19: **Collaboration between types of organizations.** Alternative projects on the left and dominant on the right.

perspective: “others” had almost exactly the same number of links to other types of institutions than mining companies did in alternative projects. On dominant projects, “others” have only a 59% of the connections that mining companies have with others. In sum, “others” play a key role in alternative, while for developments along the dominant trajectory mining companies need only the help from research institutions.

Associations don’t even show up in the dominant network. With respect to the government, it also goes from similar collaboration with mining companies and “others”, to collaborate mostly with mining companies. However, as a share of the connections universities have with mining companies, the government has a stronger participation in the alternative network, suggesting that the government might be more interested in alternative than in dominant projects. This would make sense, as alternatives usually have strong positive externalities while the benefits of dominant projects can be much more easily appropriated by the firms.

The following figure shows how these networks would look if Universidad de Chile -and its associated projects- did not exist. In the case of alternatives, the remaining projects have more collaboration with “others” than with mining companies. As suggested by some interviewees, Universidad de Chile is a name to which mining companies want to be associated, it might be more difficult for less reputed universities to secure agreements with mining companies. Another interesting difference is that internal collaboration between mining companies goes down about a third, meaning this university is effectively making mining companies connect to each other. It is good to see that internal collaboration survives, but it depends to a large extent on a single university.

Regarding the dominant projects, the structure of the network is similar, but what is interesting is that in this case, intra-mining companies collaboration stays almost exactly the same. Mining companies seem to need a nudge to come to work together for alternative projects, but not for dominant ones. Again, the dominant trajectory is simply improving what they are already doing, improving the core of their business, something which is always desirable, especially when input costs are high and copper prices high. Alternatives are only interesting when they don’t pose any risk for companies (in terms of production levels) and promise some important benefit.

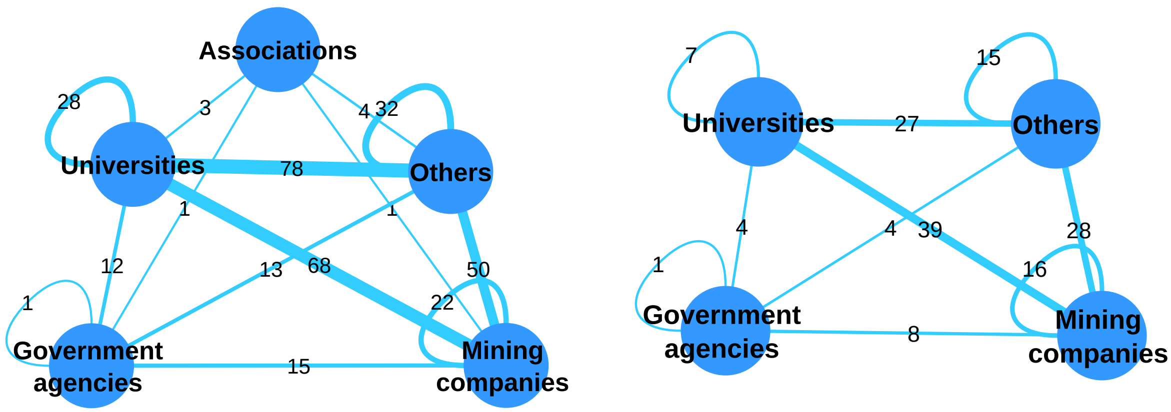

Figure 20: **Collaboration between types of organizations without Universidad de Chile's projects.** Alternative projects on the left and dominant on the right.

5.2 Evolution in time

This section analyzes the evolution of FONDEF collaboration across different time periods, to study whether there have been structural differences across them. We find some interesting -as well as worrying- results.

For this and the following sections, different mines that belong to the same company were merged together into a single node[9]. This decision was taken considering what was observed in the fieldwork: in terms of technological capabilities, mining companies should be considered as a whole, capabilities are relatively easy to transfer across several mining operations, at least in the medium and long terms[10]. Universities are also considered as single entities, but it is possible that different departments of faculties collaborate with the same companies and do not have much internal communication. We assumed that this was not the case, as we do not expect it to be like that in the majority of the cases.

We will look at three time periods: 1991-1995, 1996-2000, and 2001-2005. In the first period, it must be born in mind that FONDEF projects were awarded only in the first two years. The last project that was classified and has more than one participant was in the year 2006, but it was only one project and consisted of only two institutions.

First we will review in detail the evolution of the network of "alternative" projects, and then we will briefly look at its counterpart made of "dominant" projects.

Before proceeding to the networks, Figure 21 shows the legend of the network diagrams. Network size and edge width represent the same concepts as in previous networks. In addition, the type of organization is represented by node shape and color.

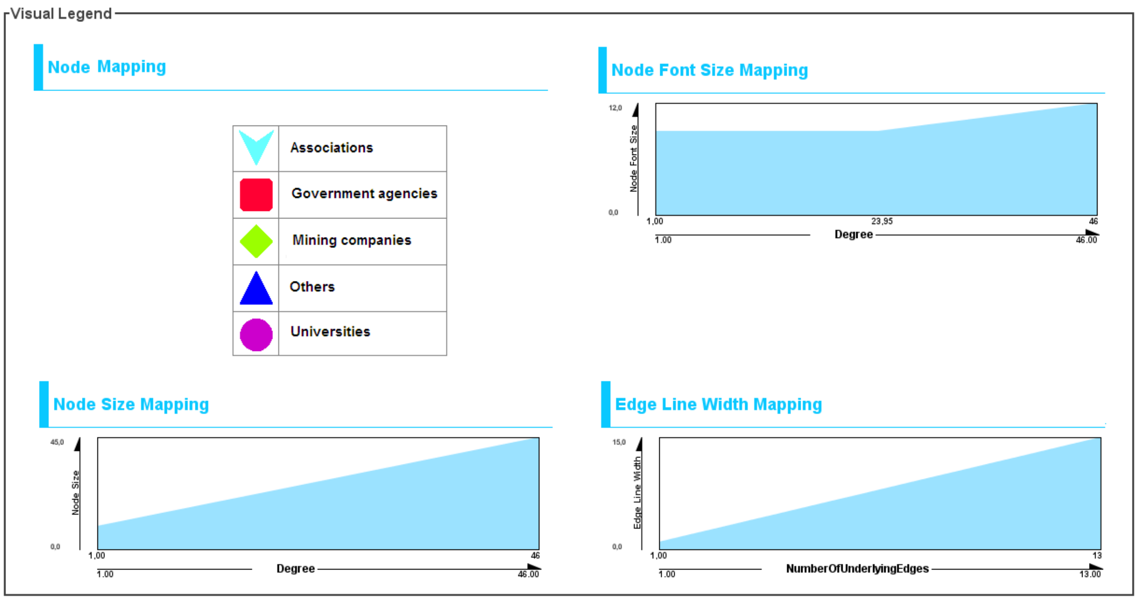

Figure 21: **Legend for the diagrams in this section**

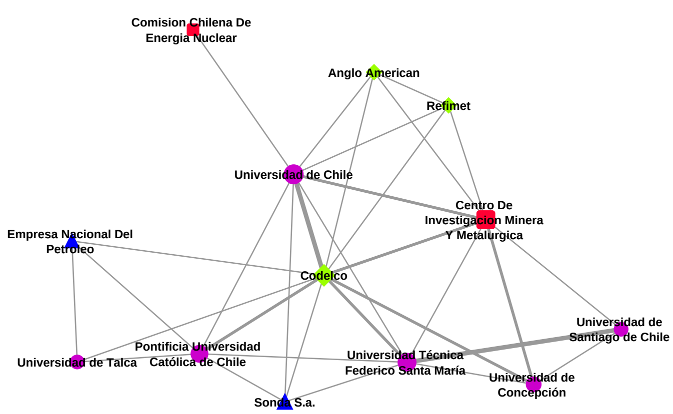

Figure 22: **1991-1995 network of alternative projects**

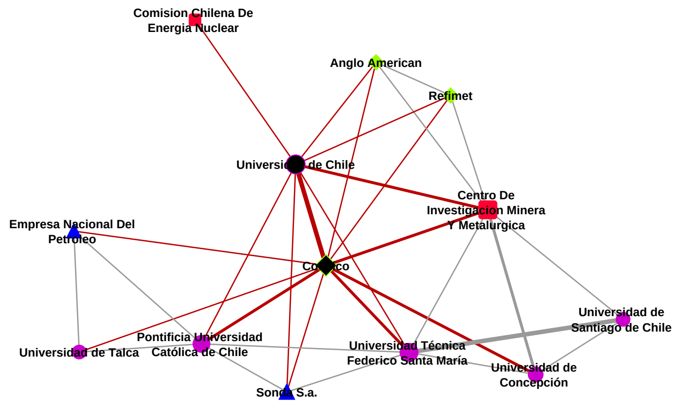

Figure 23: **1991-1995 network of alternative projects highlighting Universidad de Chile and Codelco**

5.2.1 Network of projects in alternative pathways

First period: 1991-1995

The 1991-1995 period network of alternative projects is formed with only 10 projects awarded in 1991 and 1992[11].

There is a very clear pattern, universities are the main actors, and the core of the network is formed by Universidad de Chile and Codelco, and to a lesser degree, by Centro de Investigacion Minera y Metalúrgica (CIMM[12]). Other universities also have relatively strong linkages to other institutions, most notably Codelco. Private actors play a very minor role, participating in few projects and having few connections. The bottom diagram shows how Universidad de Chile and Codelco span pretty much the whole network.

Second period: 1996-2000

The network for this period is formed by a total of 32 projects that were classified as alternative. Although tripling the previous one in number of projects, the differences among the networks are not only of scale. The first thing that strikes comparing it to the previous network is the amount of participants, but this is a direct effect of the number of projects. The next fact that becomes clear is that there is much more diversity in the agents involved. Universities are still the most important set of nodes, but the share of other types of actors has increased greatly, including more mining companies (about as many as universities, from being half as many in the previous period), more suppliers ("others"), and more public agencies.

Looking in more detail, it is possible to see that private mining companies have weak ties to other nodes, and locate themselves closer to the edges of the network. The few companies that do have

[9]"Doña Inés de Collahuasi" mine was assigned to Anglo American, although Xstrata Copper has the same participation. This was simply a methodological decision, because Anglo American had several other nodes to merge. The objective of this report is not to assign positive or negative results to particular companies.

[10]Networks with "disaggregated" companies were nevertheless built. The network parameters do not vary significantly in most cases, except for mild increases in clustering and centralization measures when companies are merged.

[11]Only projects with more than one participant are considered.

[12]CIMM could have also been classified as a "University" because of its research center nature. This would not have significant impacts on the analysis.

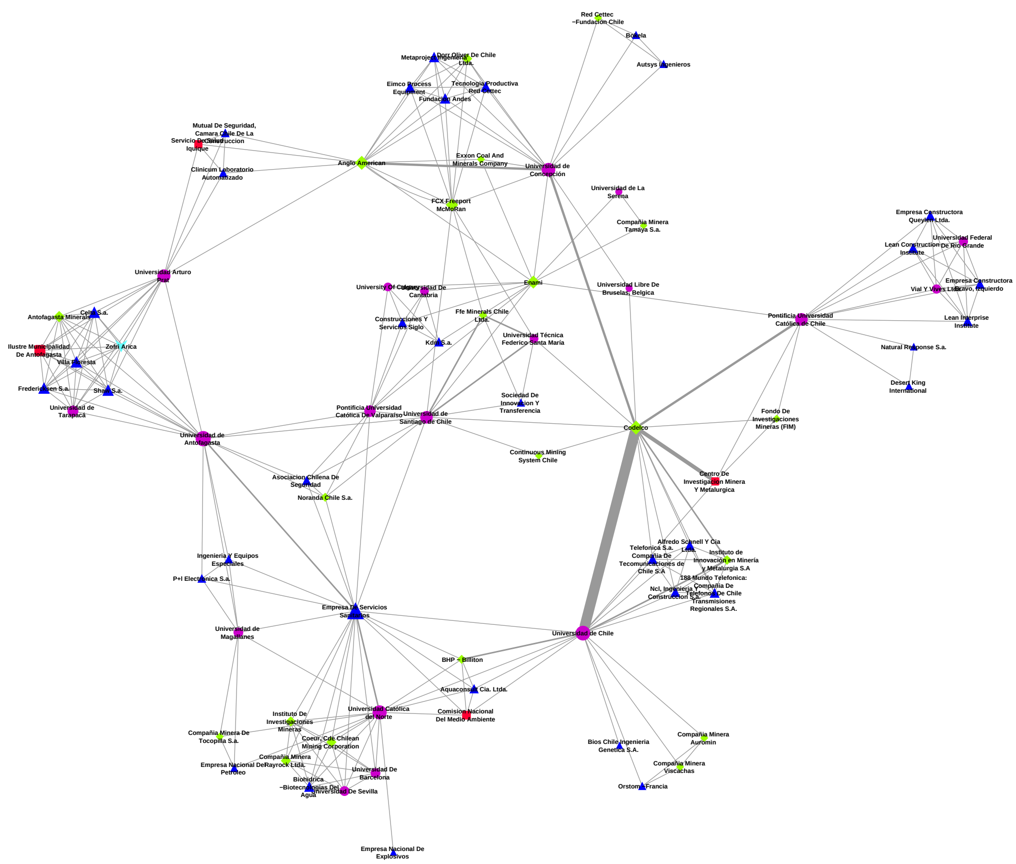

Figure 24: **1996-2000 network of alternative projects**

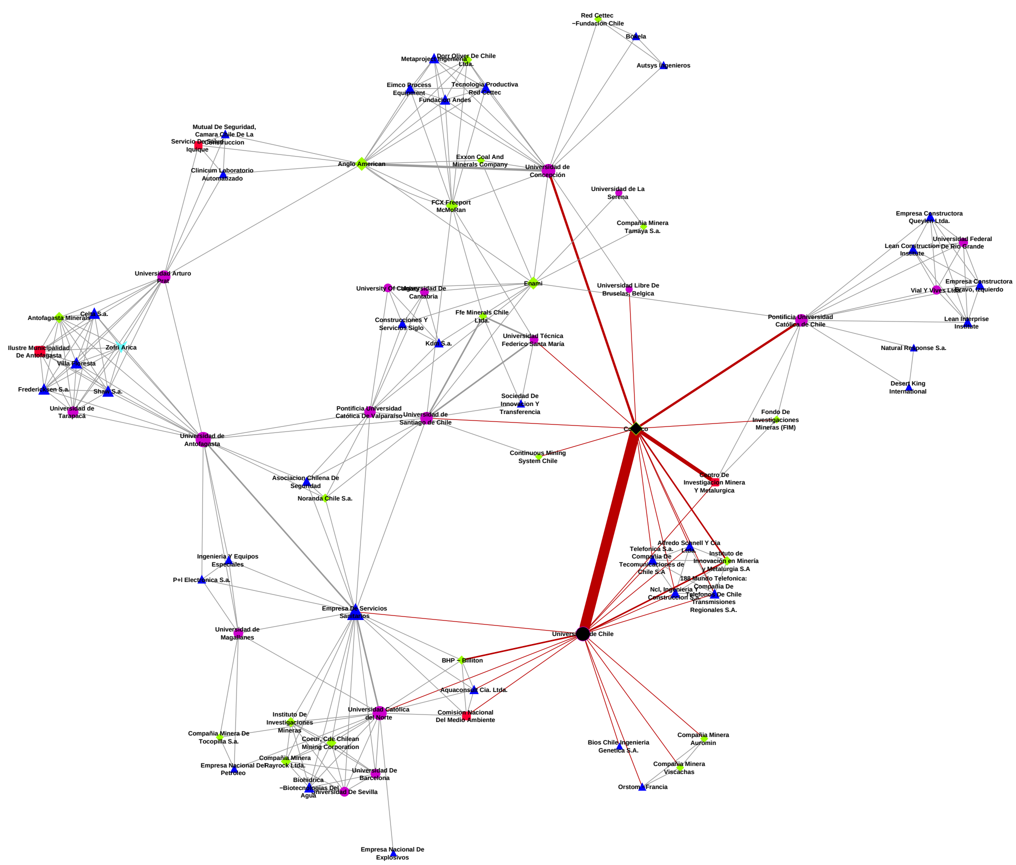

Figure 25: **1996-2000 network of alternative projects highlighting Universidad de Chile and Codelco**

strong ties to universities are located far apart from each other, each company seems to collaborate with a particular university or set of universities, without much interaction.

Another relevant fact is that universities from the northern region of Chile[13] have relatively large node sizes, meaning that they have many links to other nodes. While this might seem trivial, considering that most of copper mining occurs in this region, it is not. The high degrees of centralization in the Chilean society extend to the world of academy and research, so it is reassuring to see that regional universities are collaborating with the private sector and doing research in alternative pathways. There is however an hypothesis from one of our interviewees that should be mentioned. According to his experience, collaboration with universities is sometimes an implicit obligation for mining companies, as part of the duties needed to obtain their "social license to operate"[14].

Several of the links that existed in the previous period are maintained and reinforced, showing that trust is built between institutions (notably universities in this period) and collaboration relationships grow and improve with time. The most evident example is Codelco-Universidad de Chile[15], but other links between universities are also important. Figure 25 shows the span of Codelco and Universidad de Chile across the network. It is evident that their reach is much reduced with respect to the previous period. In 1996-2000 a much more robust network is formed, as other universities act as connecting hubs and have FONDEF projects with many more mining companies and other related companies.

One possible explanation for the large amount of projects and institutions in this period is that pending projects were accumulated during the three years without FONDEF. We disregard this hypothesis for two reasons: first, it is unlikely that interest in and resources for all potential projects would remain for several years, both at universities and firms. In fact, it is likely that as FONDEF was not available, there weren't many attempts at establishing university-firm research projects.. Second, looking at the total FONDEF projects awarded every year it does not look as if there was an "accumulation" effect.

First and second periods: 1991-2000

Aggregating the networks from the two periods, we can see a more dense network , with a core formed by Codelco, CIMM, and several universities (de Chile, Católica, Concepción, Santa María). Not all of these "core" nodes have a high *degree* (number of connections), but all of them have strong connections between them and provide connectivity to the network. The "northern" universities have relatively high *degrees*, but are for the most part disconnected from this "core".

Third period: 2001-2005

Finally, we look at the 2001-2005 period, with a network formed by 23 projects. First of all, the fall with respect to the previous period does not seem to be rebound from an "accumulation" of projects in the 1993-1995 period. The total number of FONDEF projects (in all disciplines) does not fall relative to 1996-2001.

This period presents a strong participation of public agencies and "others", and few mining companies. By far the most important ones are the public ones, Codelco and ENAMI. Among the private companies, only Anglo American has a relatively central network role, and BHP-Billiton also participates but in a small number of projects.

Universidad Católica de Chile leads a project that forms a network component separated from the rest, something that did not happen in previous periods. Compared to the 1996-2000 network, that showed a relatively robust structure, in this period again Universidad de Chile and Codelco span a large share of the network, and together with Anglo American and ENAMI, are the only actors keeping

[13] Universidad Católica del Norte, Universidad de Antofagasta, Universidad Arturo Prat.

[14] There is yet another reason for establishing links with universities: being recognized by students and obtaining their "loyalty", something critical under the current shortage of professionals. But this crisis has been more profound during the last couple of years, so it shouldn't play a very large role in the period we are studying.

[15] Many projects between them are *exclusively* between the two, building a strong relationship but only indirectly feeding the network, through their shared learning.

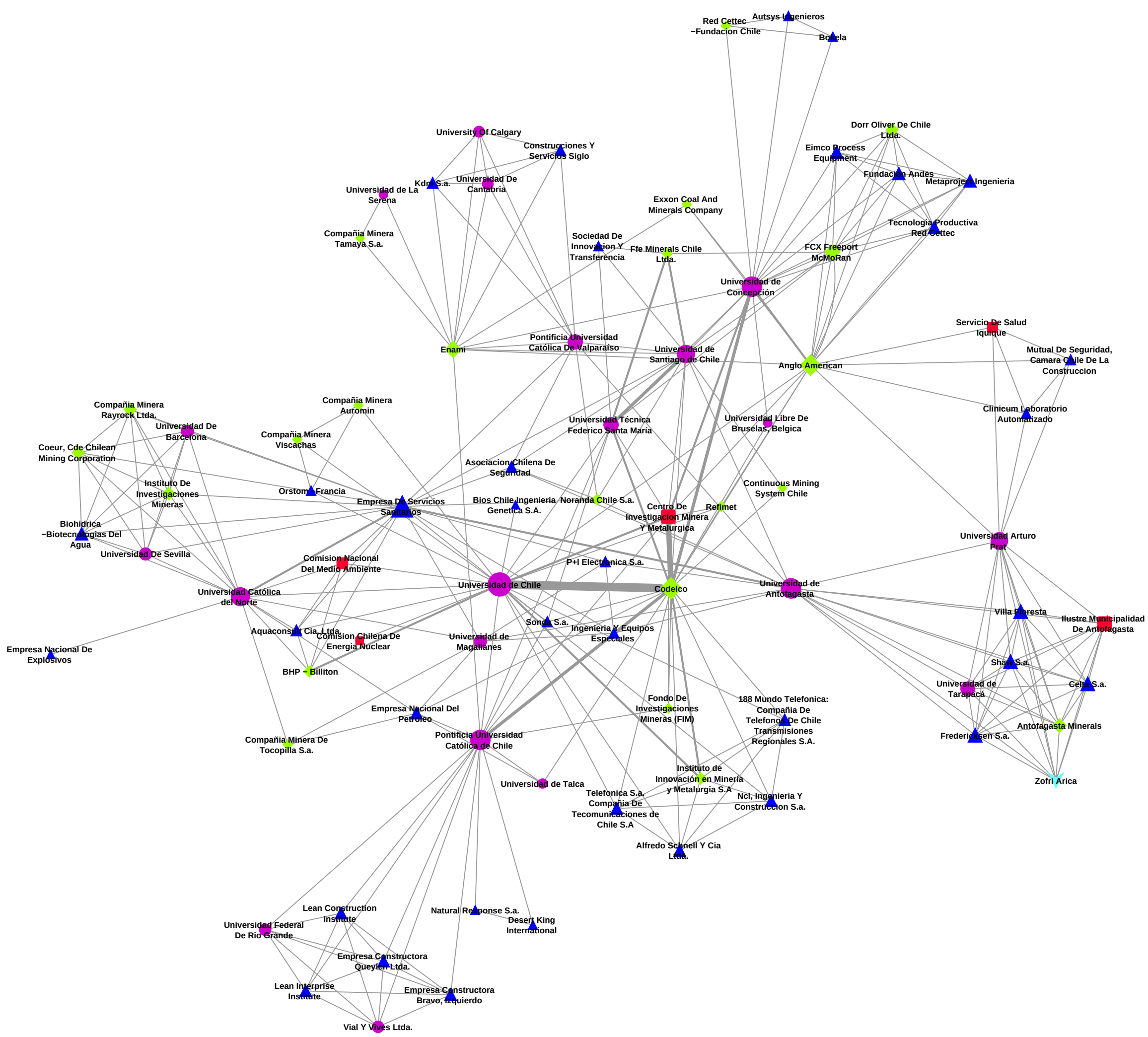

Figure 26: **1991-2000 network of alternative projects**

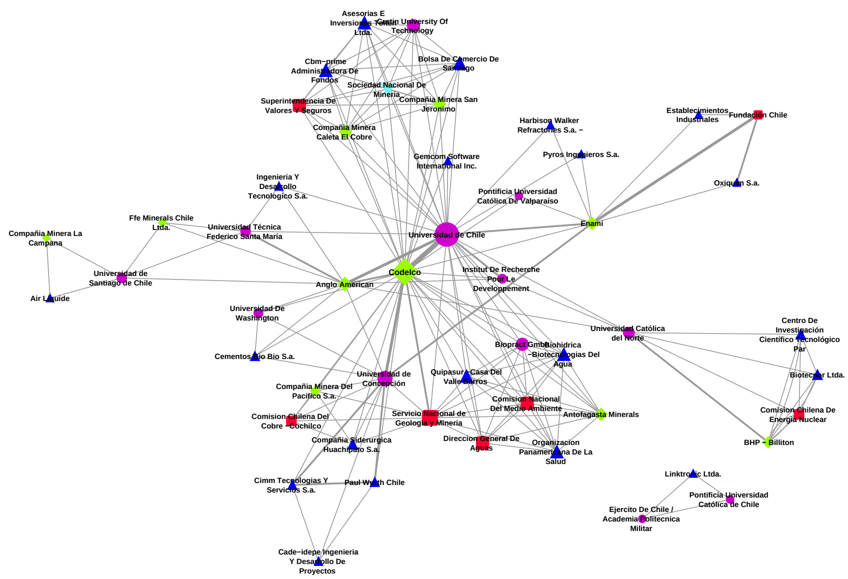

Figure 27: **2001-2005 network of alternative projects**

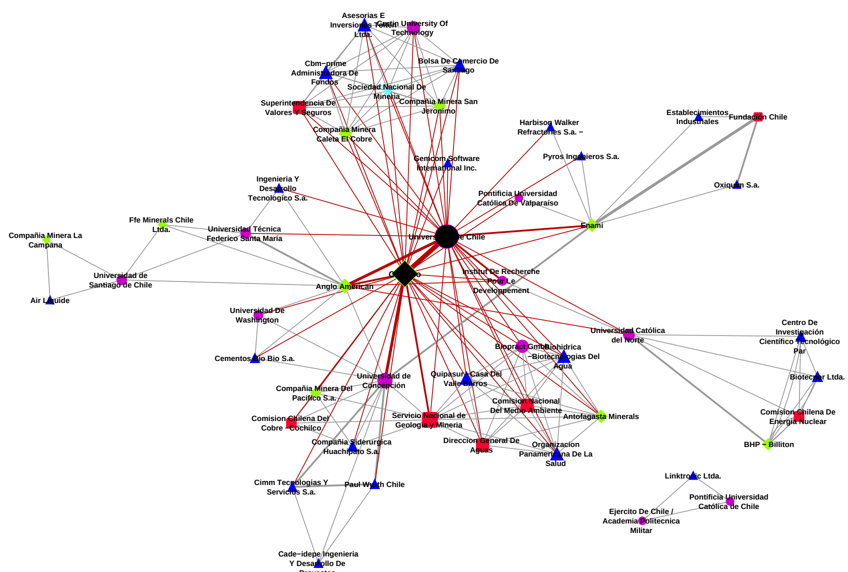

Figure 28: **2001-2005 network of alternative projects highlighting Universidad de Chile and Codelco**

the largest component of the network in one piece. The network looks like three independent projects with large groups of actors (the clusters observed in the edges), independent projects between groups of 2 or three institutions, and all of those connected by a couple of really-connected actors.

In sum, what seemed like a very positive evolution from the 1991-1995 to the 1996-2000 period is completely reversed in 2001-2005. Eventually, if this structural differences were the natural result of the networks constructed with different amount of projects, the question still remains: why the amount of projects has decreased? It is not the result of an overall decrease in FONDEF funding (there were 405 projects in 1996-2000, and 421 in 2001-2005). It is not a decrease in the share of projects classified as alternative, that actually increases in the third period (from 88% to 94% of the analyzed projects). It is not an increase in the rejection of FONDEF applications[16]. There seems to be a fall in the application for FONDEF funding in the mining sector. This could have negative or positive interpretations. Negative could be that interest in doing research and collaboration, particularly along alternative pathways, decreased in that period. It could also be that mining companies had relatively negative experiences working with universities (something suggested during the fieldwork), so they simply dropped out of these kind of projects afterwards. A more positive view is that projects could be moving towards firm-level innovation funding lines, or simply to private funding, as the magnitude of public funds might "not be worth the hassle" for large mining companies.

Complete period: 1991-2005 and network evolution

The network for the whole 1991-2005 period is based on 65 alternative projects with more than one participating institution. In the complete network, universities, followed by public agencies, appear as the largest and more centrally positioned nodes[17]. There are many mining companies, but by far Codelco is the one with more connections and the most central position. Antofagasta Minerals and Anglo American appear as the private mining company more relevant for the network structure.

Network theory parameters can be used to look at the evolution of the network in more detail. For both Codelco and Universidad de Chile, the *average shortest path* to other nodes almost double and then decreases back to almost the initial level when going from the first to the second and then to the third period. In other words, in the second period the rest of the network is further away from them, and is pretty close in the first and third periods. The *betweenness centrality*, related to how a particular node helps connect other nodes, decreases slightly and then increases, to reach a level even higher than in the first period in the third one. These parameters show how their role was reduced in the second period, but in the third period, some measures show a network even more dependent in just these two nodes.

Nevertheless, when looking at the complete 1991-2005 network there are clusters connected through other universities, such as Católica (though without mining companies), Católica del Norte, Antofagasta, Arturo Prat, and Concepción. Among private mining companies, Anglo American and BHP-Billiton have some strong linkages. Both have them with Universidad de Chile, and Anglo American with Universidad de Concepción (and to a lesser degree with Santa María), and BHP-Billiton with Católica del Norte, although not too strong. Antofagasta Minerals is connected to many universities, but no link is strong, not even to Universidad de Chile. Out of the regional universities, Universidad Católica del Norte and Universidad de Antofagasta have the highest *degrees*, although most of their connections are weak.

Network theory measures for the whole networks -rather than node-based measures- can also be used to compare the networks from the three periods. The *number of nodes* increases more than proportionally with the number of projects in the second period and stays relatively large in the third period. At least the number of participants per project seems to stay high in the third period, a good sign for collaboration. *Network radius* increases and then decreases. *Centralization* moves strongly in the direction expected: it drops from 0.5 to 0.16, but then goes back to 0.49. Something similar

[16]This results are unreported. The share of approved projects has increased for both dominant and alternative projects, although it is highly volatile in a yearly basis.

[17]Most of the references to centrality refer to *betweenness centrality*.

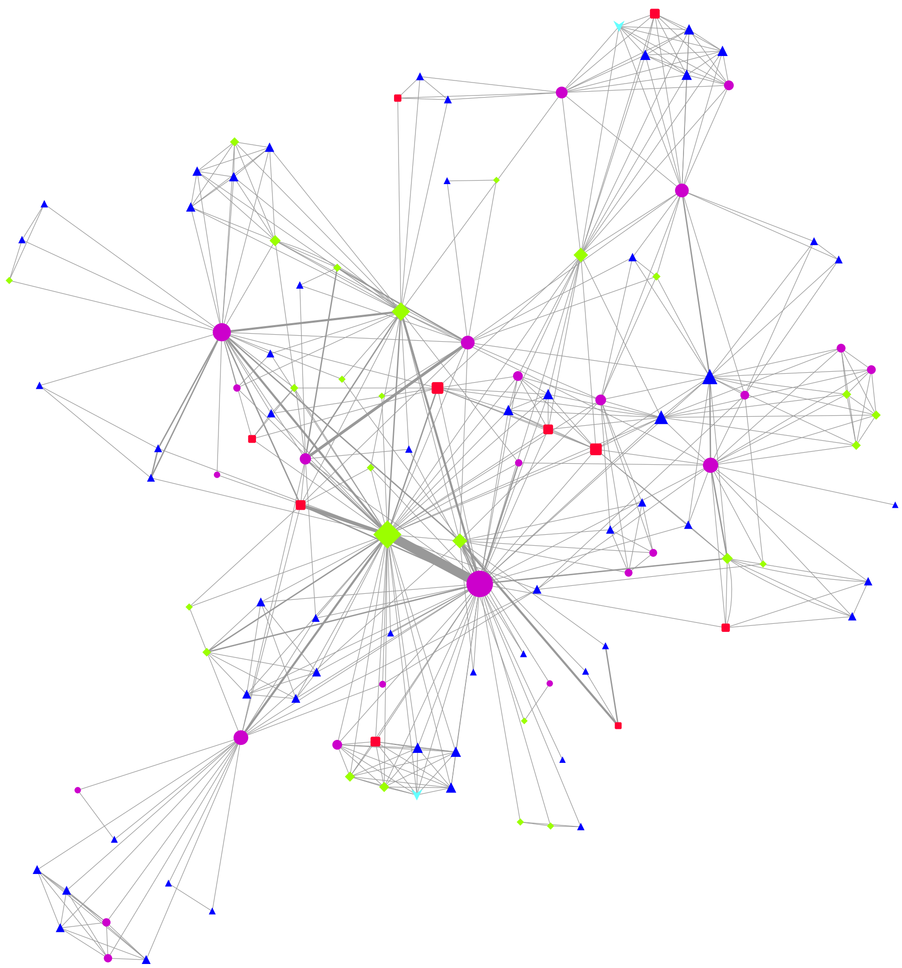

Figure 29: **1991-2005 network of alternative projects (without labels)**

		Average Shortest Path Length	*Betweenness centrality*
1991-1995	*Codelco*	1.167	0.295
	Universidad de Chile	1.333	0.217
1996-2000	*Codelco*	2.202	0.228
	Universidad de Chile	2.367	0.213
2001-2005	*Codelco*	1.489	0.336
	Universidad de Chile	1.511	0.357

Table 3: **Some network measures for Codelco and Universidad de Chile in the different periods**

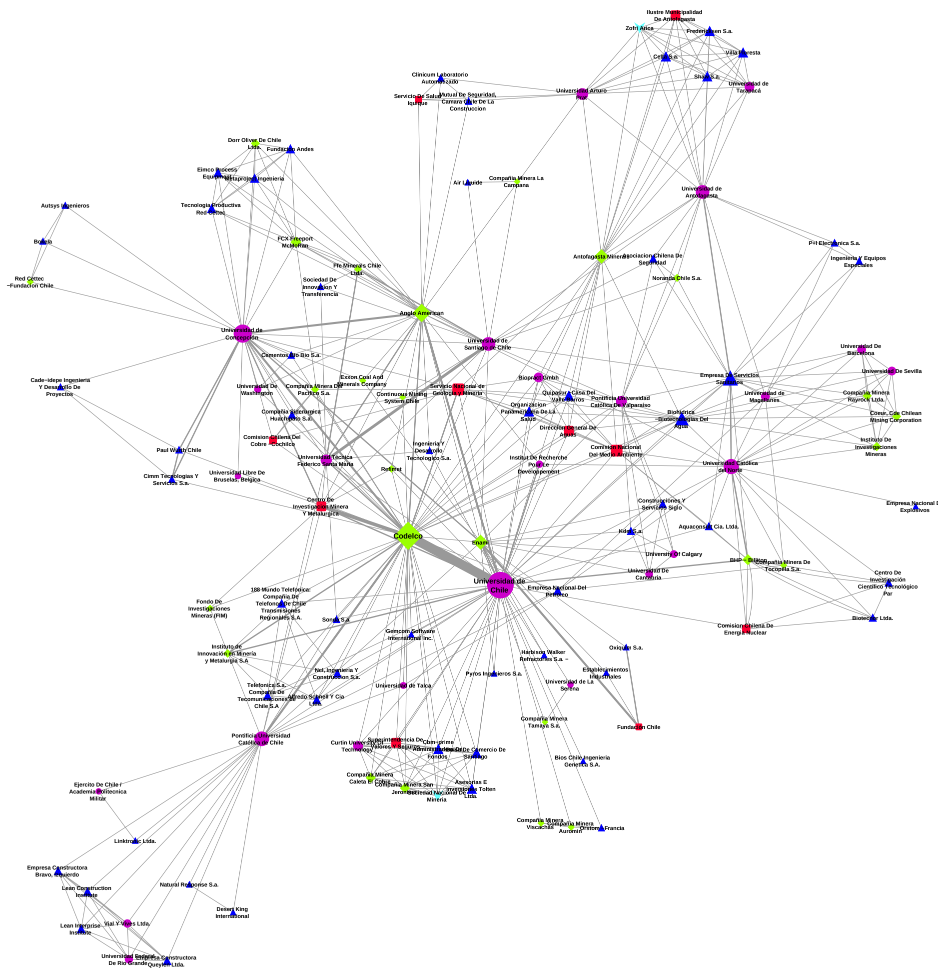

Figure 30: **1991-2005 network of alternative projects**

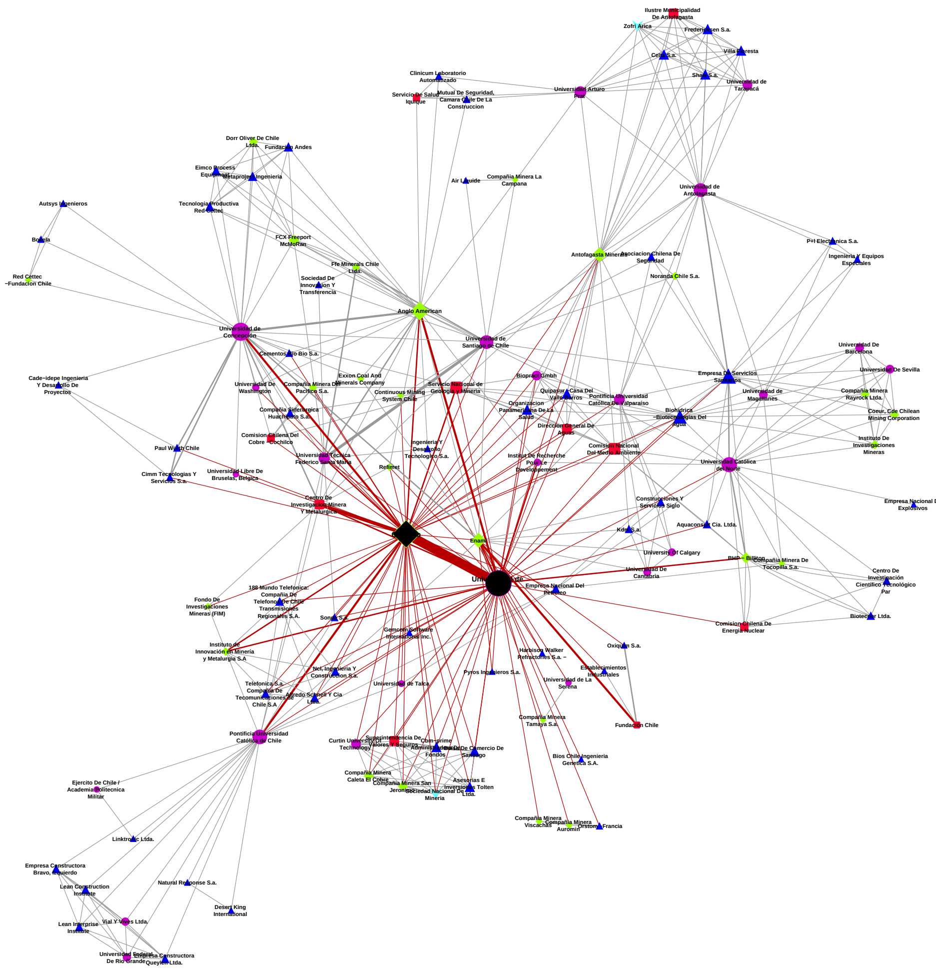

Figure 31: **1991-2005 network of alternative projects highlighting Universidad de Chile and Codelco**

	1991-1995	*1996-2000*	*2001-2005*
Clustering coefficient	0.726	0.851	0.873
Network radius	2	3	1
Network centralization	0.5	0.162	0.487
Number of nodes	13	80	51
Network density	0.410	0.083	0.133
Network heterogeneity	0.488	0.586	0.808

Table 4: **Network measures for the different periods**

happens with *network density*. Its relatively mild increase in the third period is possibly associated to the large amount of nodes (and therefore total possible connections) in the third period vis-à-vis the first. Finally, *network heterogeneity*, a measure of the tendency to form network hubs, is monotonically increasing.

Finally, we considered whether the networks behave as "scale free" networks. One of the robust findings of complex networks researchers is the fact that many natural and artificial networks, of very different kinds, have power law (i.e. Pareto) degree distributions (the probability distribution of degrees over the network). In this case, none of the networks behave in this way. One possible interpretation is that these collaboration networks simply don't display this widely found property. Another, more controversial interpretation, is that these networks are not being formed in the "natural" way that collaboration networks tend to form, and instead, they are somehow being "forced" into their actual structures. Figure 32 clearly shows than none of those degree distributions could possibly be described by Pareto distributions.

On the other hand, Figure 33, the degree distribution for the whole period, at least gets closer to being a monotonically decreasing, fat tailed distribution. There is a small group of very well-connected nodes, another group of many nodes with a small number of connections, and a third, intermediate group. It is also a possibility that the network is only beginning to converge to a "scale free" network as more and more nodes are being added[18]. This could be consistent with a somewhat "forced" or random network in the first periods, with many information, knowledge and resource asymmetries between the different public actors, private actors, and universities in terms of application to public funds and technological capabilities. While these asymmetries would not all disappear as time goes by, they could be acting as transaction costs that difficult the natural formation of networks.

Without Universidad de Chile

Finally, we conduct the experiment of completely removing all projects where Universidad de Chile participated, and look at the 1991-2005 network again[19]. The number of nodes fell from 119 to 88, a striking 26% of actors disappear if we assume that it was Universidad de Chile that brought them to the networks through its FONDEF projects.

Unreported results show that *centralization* and *heterogeneity* (tendency to have hubs) both fall significantly: we have a more distributed network. *Clustering* almost doesn't fall, possibly the groups formed by other universities keep the clustering structure of the network similar. The *average path length* (across nodes of the network) does increase when Universidad de Chile is gone, but not dramatically, about a 10%. In other words, it doesn't get much longer to travel across nodes, Universidad de Chile was not so critical in this respect.

However, the impact should also be considered in terms of knowledge generation: it could be the case that some of the projects that stay in the network would have trouble being developed if they

[18]Another problem is whether connections made 20 years ago are still relevant in terms of trust and accumulated capabilities; for some cases they probably are, and for other not. In other words, not always it makes sense to lump all edges together in a single network.

[19]The network layout is redrawn, so the networks should be looked at carefully to compare them.

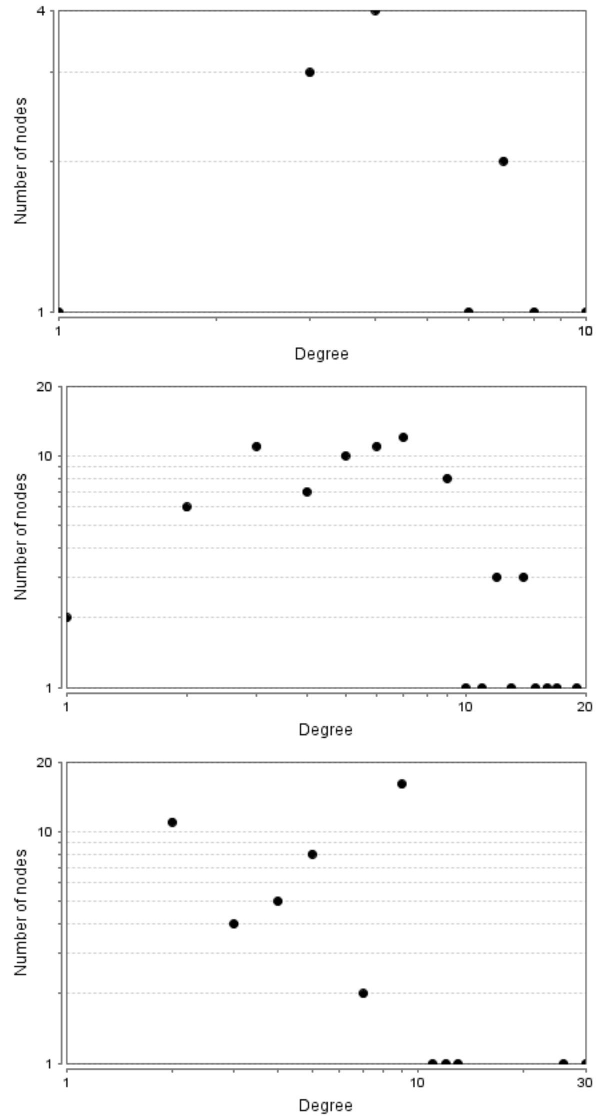

Figure 32: **Degree distributions for the 1991-1995, 1996-2000 and 2001-2005 networks**

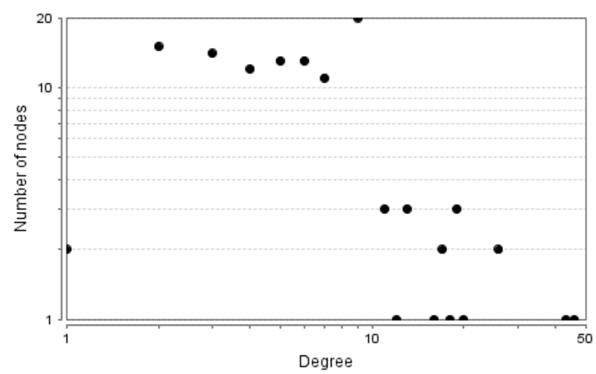

Figure 33: **Degree distributions for the 1991-2005 network**

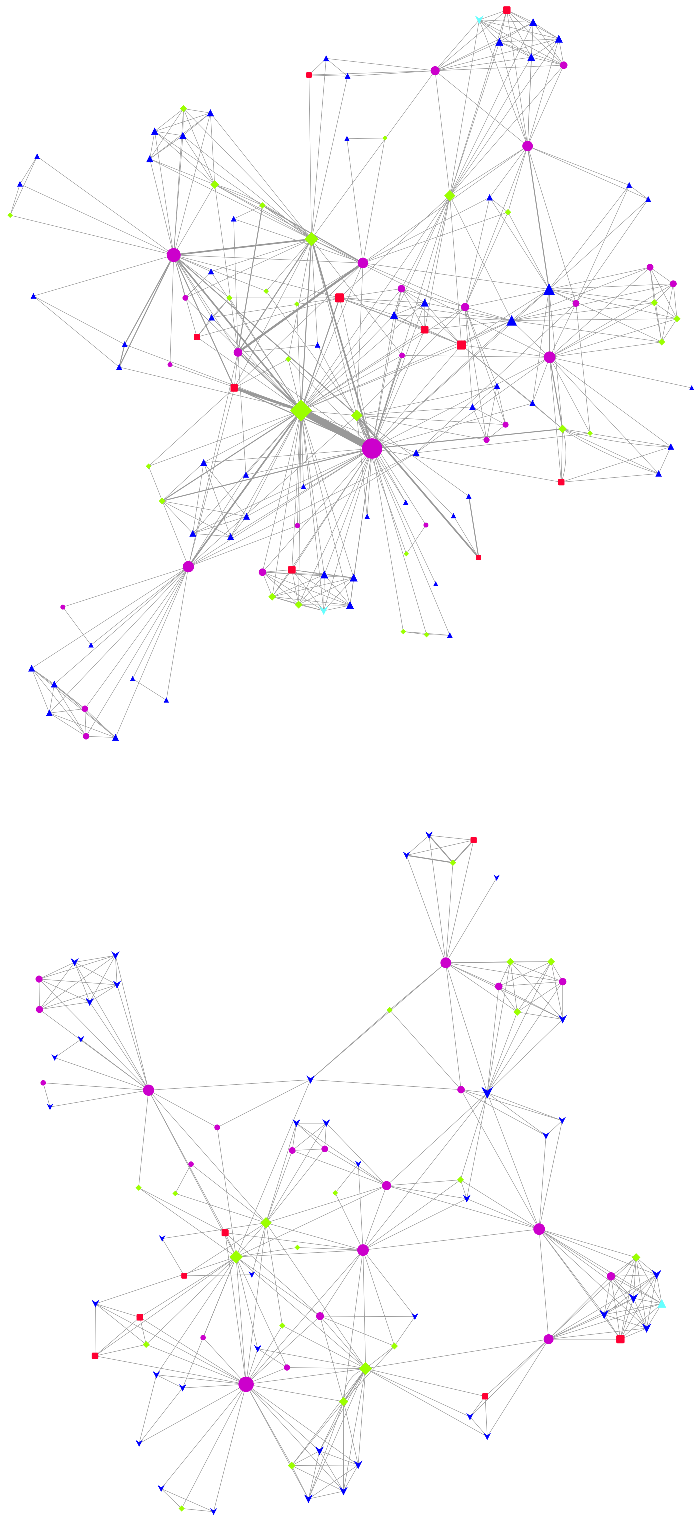

Figure 34: **1991-2005 network with and without Universidad de Chile** (completely removing all projects associated to it)

depended in part in knowledge generated by the projects that were simulated out of the network. The only way to know this potential impact of particularly important nodes would be to look in detail at projects in particular pathways.

Another fundamental node in the network is Codelco. Although we do not conduct the same experiment as for Universidad de Chile -given our assumption of the incentive to start projects being on the side of research institutions- it is safe to hypothesize that if Codelco did not participate the development of alternative pathways would be deeply hurt. It is evident from all the figures that the participation of Codelco in FONDEF projects is much stronger than that of other important mining companies. One possible explanation, given our fieldwork findings, is that some people inside Codelco has been worried about national competitiveness, and seen a role for Codelco beyond simply providing the Treasury with funds every year. As they don't see private companies doing as much as they could in terms of fostering research and innovation, they feel the need for publicly owned Codelco to take that role. It is interesting that -as someone pointed out in an interview- Codelco is not really saving any money by obtaining public funds...it is just public funds moving from one place to another. This reinforces the idea that Codelco is "helping" universities and suppliers develop new technologies and capabilities. There is another factor that could contribute, the "social license to operate". As mentioned before, collaboration with universities might be part of the "social pact" between companies and communities. Codelco, with its span across the country, needs to worry not only about local communities, but about the society as a whole, and this might move the company to have high levels of collaboration with universities.

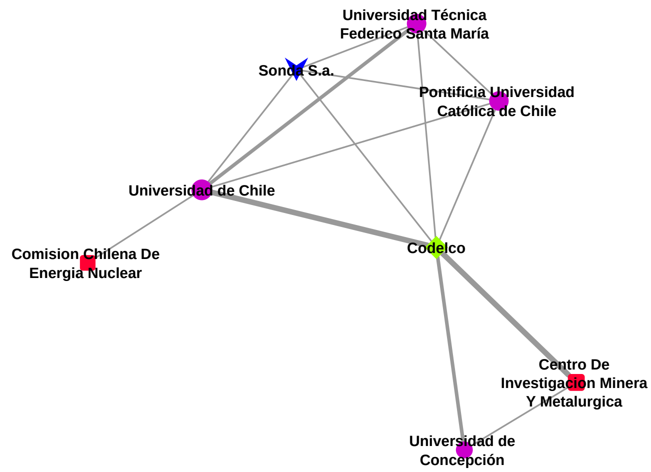

Figure 35: **1991-1995 network of dominant projects**

5.2.2 Network of projects in the dominant trajectory

We will look more briefly at how the network of projects classified as dominant[20] has evolved in the same period. As before, here mining operations were merged into mining companies as single nodes.

1991-1995

In the first period we see a small network (formed by only 5 projects), where Universidad de Chile and Codelco play important roles, and where no private companies show up. In this sense, it is very similar to its counterpart in alternative projects.

1996-2000

In the second five-year period, the network grows (just like for alternative projects) and is formed by a total of 15 projects, and it also looks relatively more robust, although with a disconnected component. What could be the main difference between our networks of alternative and dominant projects develops in this period: Universidad de Concepción, rather than Universidad de Chile, is the most central actor of the network, followed by Anglo American and Codelco. Universidad de Concepción is recognized as a leader in the area of metallurgy, and this might be the cause of its centrality in dominant projects. Private mining companies are very prominent in this network. While in the first period private mining companies are just beginning their operations in the country, for this period they are already established and they collaborate both between them and with universities.

An important difference with the alternative network in this period is the importance of "others" (suppliers). In the alternative network they were not necessarily central, but many of them participated. In the dominant network there are just as many "others" as mining companies. In the alternative network, there are around three "others" every two mining companies.

2001-2005

In the third period, there are less nodes (29 down from 37 in the previous period), but the amount of projects increases to 16, in contrast with the sharp fall in alternative projects in the same period.

[20] Here *all* projects classified as dominant are considered, no matter if they also qualify as alternative in some dimension.

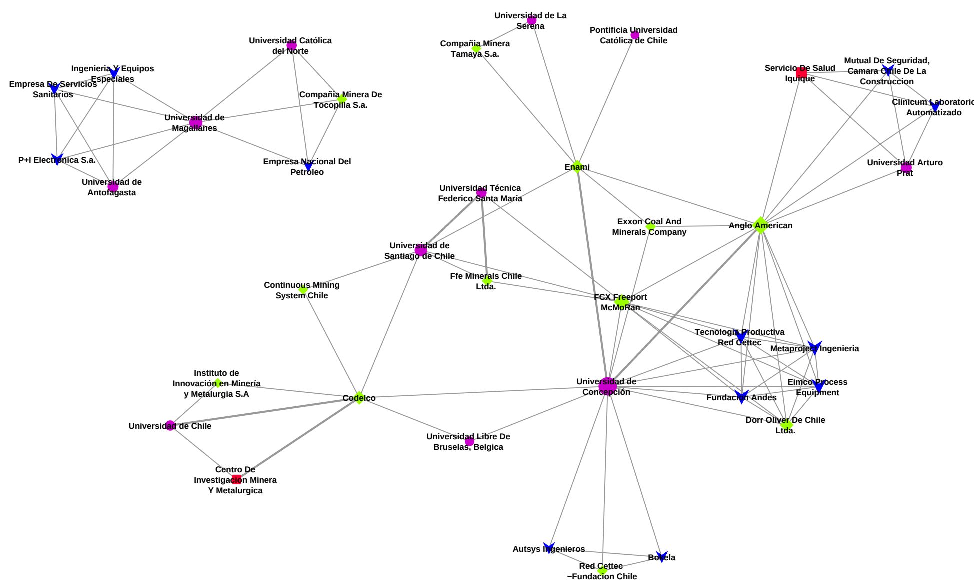

Figure 36: **1996-2000 network of dominant projects**

This is a fundamental difference, that reinforces the idea that mining companies might be less prone to participation in alternative projects than before, but have kept interest in improving the dominant trajectory[21]. Another remarkable difference, comparing to the alternative network at the time, is that public agencies are only marginal in the dominant network. Moreover, there is less collaboration, as we have relatively the same number of projects but a reduction in the number of participants.

As the alternative network, this one tends to become more dependent in a few actors. The difference here is that it is Anglo American, and then Codelco and Universidad de Concepción that are the most central actors.

Complete period: 1991-2005

Finally, we look at the network of all projects classified as dominant, that should be compared with that on Figures 29 and following.

The network is built with a total of 36 projects, and is composed of 58 nodes, compared to the 65 projects and 119 nodes in the alternative projects in the same period.

The first obvious difference between the two networks is the size. But besides this, it is interesting that while Codelco and Universidad de Chile still have a high level of bilateral collaboration, they are not as central as in the alternative network. In the dominant network, they are replaced as the most central actors by Anglo American and Universidad de Concepción, that form an axis parallel to them. Universidad de Concepción has also a very strong link to Codelco in dominant projects.

In terms of the participation of different kinds of actors, public agencies seem less central, something consistent with more interest from the public sector in alternative pathways and from the private sector in the dominant regime. Suppliers ("others") and mining companies are present in roughly the same

[21] In our initial characterization of evolution in time, in Section 3, we did not observe this. There we had a larger universe of projects, here we only consider those for which we have data about all participants. But looking in more detail at the complete database, we see that the number of projects fall, but the share of both projects classified as alternative and as dominant increase, however the latter increases much more. This is consistent with an increase in importance of dominant projects. The initial characterization looks only at absolute numbers of projects, where the divergence is not evident. There is still, however, some discrepancy between the two datasets that is difficult to clarify without more information about their construction.

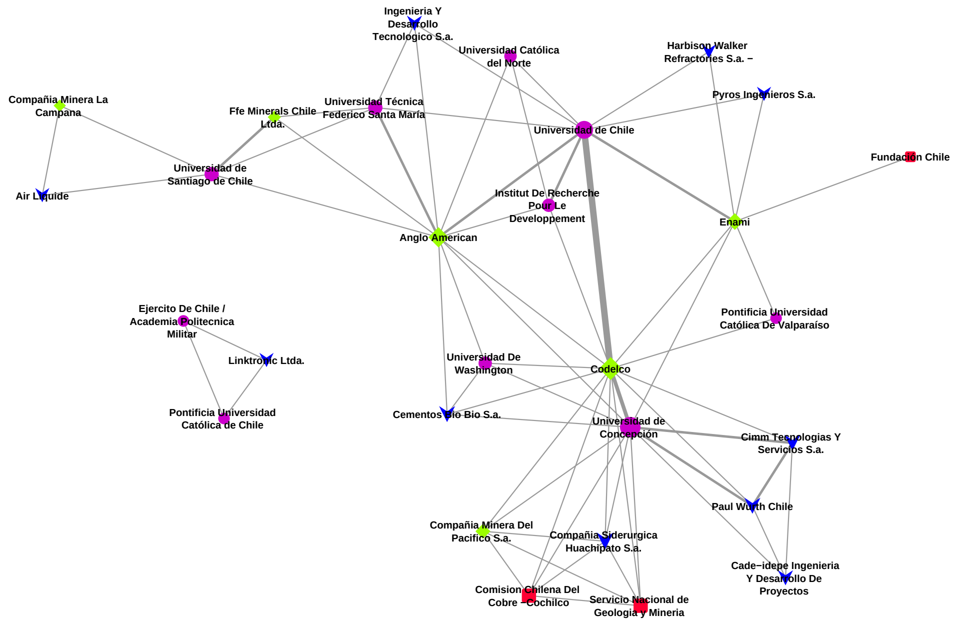

Figure 37: **2001-2005 network of dominant projects**

	Alternative	*Dominant*
Clustering coefficient	0.860	0.825
Network radius	3	3
Network centralization	0.332	0.338
Number of nodes	119	58
Network density	0.063	0.094
Network heterogeneity	0.922	0.909

Table 5: **Network parameters for the alternative and dominant networks, 1991-2005**

number in the complete dominant network, while the former more than double the latter in the alternative one.

The degree distribution although far from monotonically decreasing, is far more close to a Pareto distribution than the network for alternative projects in 1996-2000, which is formed by a similar amount of projects. This would be consistent with the idea that the alternative network is being "forced" and the dominant one would have a more "natural" formation. But these comments should be taken with caution, as none of the distributions is really "scale-free". In terms of network theory parameters, the dominant network is remarkably similar to the alternative one, as shown in the table.

When the exercise of removing Universidad de Chile is performed, the resulting network has two components. Perhaps more important, all of the remaining edges are thin, meaning that each pair of institutions has just one or two projects together. The relevance of this comes from the trust and experience that develops when working together, that makes it possible to achieve better results in any kind of collaborative endeavor.

On the other hand, the number of nodes falls only from 58 to 50, about half of the fall seen in alternative projects in terms of percentage (from 119 to 88, a 26%). It must be considered though that Universidad de Chile was not as central in this network in the first place. However, this is still

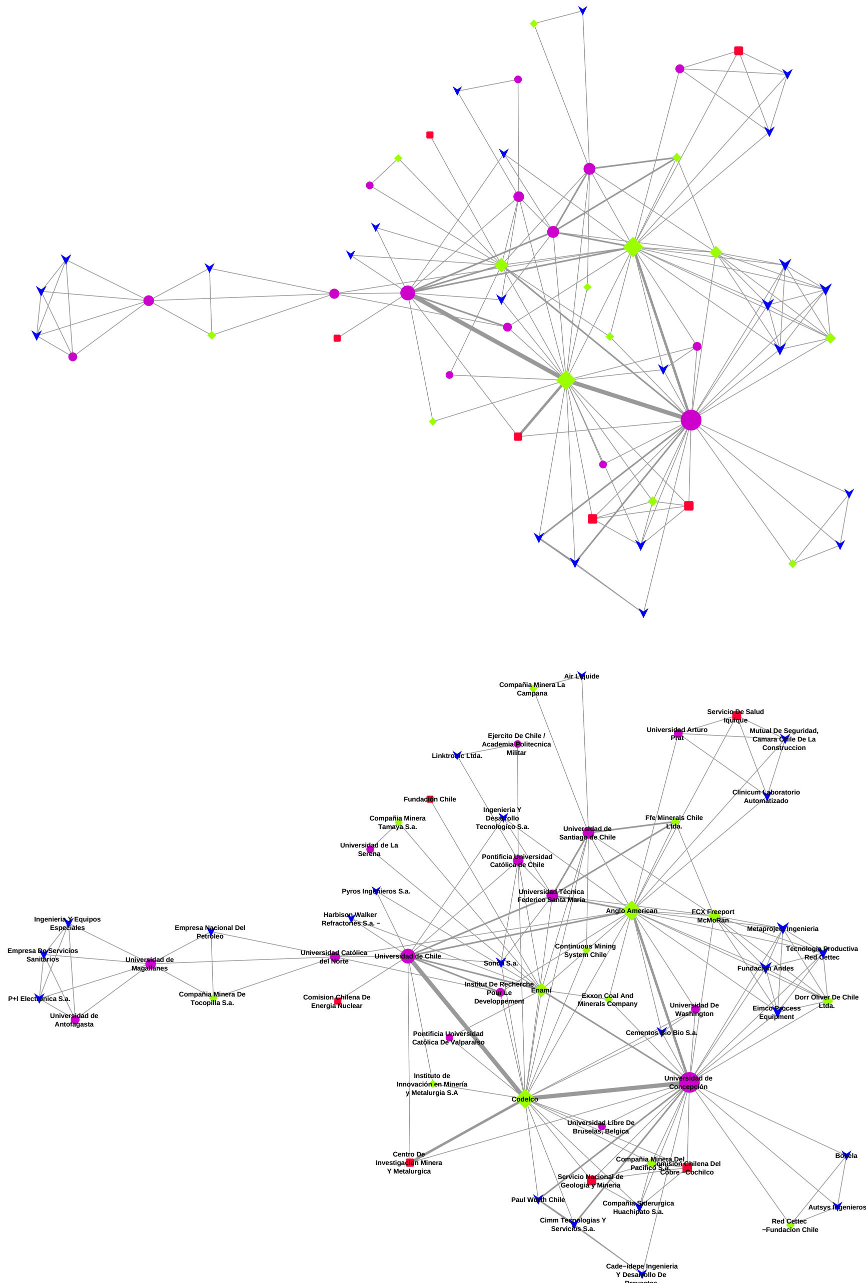

Figure 38: **Dominant projects in 1991-2005**

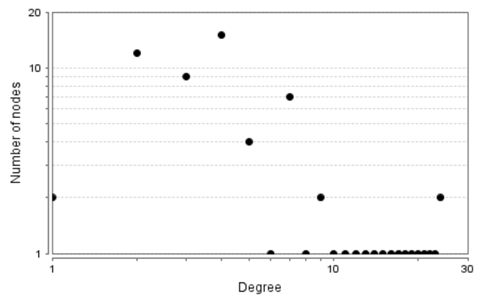

Figure 39: **Degree distribution for the 1991-2005 network of alternative projects**

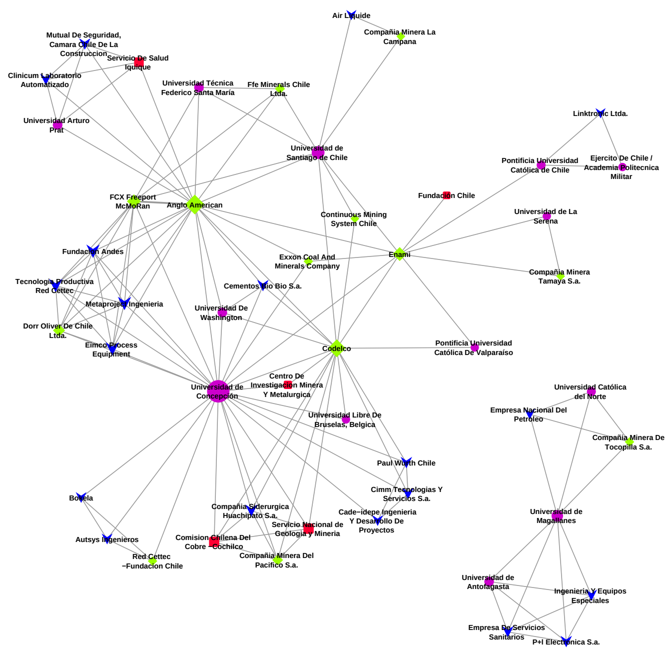

Figure 40: **Dominant projects in 1991-2005 without Universidad de Chile**

consistent with the mining companies having more interest in projects in the dominant trajectory: they are more likely to collaborate with other actors, without the reputation of Universidad de Chile, when the issue is related to the dominant regime.

5.3 Sub-categories of problems

This final section will show and comment the collaboration networks for each problem category and its subcategories.

5.3.1 Participants by subcategories

First of all, we will briefly review how many institutions participate in each type of project. On average, there are 2.94 institutions per project, and the median is of two institutions. However, there is great

Mean	2.94
Median	2
Standard deviation	2.19

Table 6: **Number of institutions per project**

		Mean	**Median**	**Mode**	**Std.dev.**
Dominant	**Total**	2.87	3	3	1.64
Economic	**Total**	2.90	2	1	2.10
	Biotechnology	4.67	4	2	3.04
	Development of suppliers (in general)	2.54	1	1	2.60
	Lack of research	2.76	1	1	2.59
	Others	3.33	2	2	3.44
	More connections across actors	3.20	2	1	2.63
	Knowledge intensive suppliers	2.92	3	1	2.00
	Alternative uses for copper	2.75	2	2	2.22
Environmental	**Total**	3.79	3	3	2.42
	Water pollution	4.86	3	2	3.18
	Air pollution	3.67	3.5	3	1.75
	Soil pollution	4.00	4	-	2.00
	Others	3.00	3	5	1.79
Productive	**Total**	2.64	3	3	1.57
	Decreasing ore grades	2.83	3	3	1.83
	Energy availability	2.40	3	1	1.34
Social	**Total**	4.44	4	3	2.55
	More or better employment	3.50	3.5	-	0.71
	Improving quality of life	7.00	6	-	2.65
	Job safety	3.83	4	5	1.83

Table 7: **Number of participants in each sub-category**

heterogeneity across categories and subcategories, as shown in Table 7.

The more remarkable cases are those of environmental and social problems, with a significantly higher number of participant organizations. Even if volatility is also high in those categories, the medians are a relatively robust indicator that in these categories more institutions participate in FONDEF projects (although the number of "social" alternative projects is quite small). The number of participants in projects related to quality of life is particularly high, something that makes sense if the projects are oriented at the local communities, the involvement of more organizations might be required to socially validate the projects.

On the other hand, there is a large number of projects in the "economic" category, but with relatively few participants. This difference might be related to a higher degree of appropriability of results than on environmental and social projects. The notable exception in the number of participants in "economic" projects is biotechnology. This is positive if we consider a general purpose technology is being developed with the collaboration of multiple actors. However, one of our case studies, a successful biotechnology start-up (more successful than universities doing research in the area), works quite isolated from the rest of the domestic biotechnology firms and laboratories.

5.3.2 Economic problems

One caveat before analyzing the networks of collaboration related to economic alterantives. It is reasonable to expect that other public instruments might be more appropriate to some of the subcategories considered here. For example, the "lack of research" problem might be more related to basic-science funds, such as FONDECYT. On the opposite end, the development of suppliers and novel knowledge intensive technologies, might be better suited for firm-level innovation funding lines. Nevertheless, we did find a significant amount of projects related to these "path-creating" alternative pathways.

The network of "economic alternatives" is built by the links found in a total of 62 projects. Looking at the unlabeled network in Figure 41, it is possible to see variety in its composition, with many suppliers, public agencies, mining companies and universities. Only a few of the latter have high degrees, and most mining companies' nodes look especially small, compared to some universities and public agencies. Looking at who are who, Universidad de Chile and Codelco form the core of the network, together with other universities and Anglo American. Two public agencies, CONAMA (environmental evaluation of projects) and SERNAGEOMIN play relatively important roles.

Compared to the findings from the previous sections, universities from the North of Chile do not have a very high participation in this network, except for Católica del Norte, with a relatively strong link with BHP-Billiton.

The network of projects related to the "lack of research" problem is formed by 12 projects, and has an interesting structure compared to the ones seen before: it has four disconnected components, each formed by just a couple of projects. It could be the case that groups of institutions are coming together to form high-quality research centers, but these groups are not connected between them. As expected, Codelco is in the groups with Universidad de Chile, and Universidad Católica de Chile forms a group without mining companies.

The network of "knowledge intensive suppliers" is the largest of all the networks of sub-categories of problems, and is comprised of 54 projects and 89 nodes. Although sometimes hard to discern, there were many FONDEF projects that were directly oriented to form knowledge intensive firms, or where important knowledge and technology were developed that had the potential of being commercialized.

Here the same pattern than in the general economic network is observed regarding northern universities. Only one of them (Católica del Norte) has any importance at all in the network. The most likely explanation is that knowledge-intensive activities are still concentrated in Santiago.

Codelco's high degree, together with its amount of connections to actors besides Universidad de Chile is consistent with the hypothesis that it is "helping" the development of knowledge intensive activities.

The biotechnology network is formed by 8 projects, with a higher number of participant per project that other networks in this category. This results in a relatively small and dense network.

A notable fact is that Universidad de Chile and Codelco are not as important as in most other networks[22]. Biotechnology could be an area where private mining companies are in fact investing and doing research, because of its potential for increasing production levels and reducing environmental problems.

It is also interesting to see that the national environmental agency, CONAMA, has a high degree in this network. This could be because of the number of water-related projects done in this field.

The company we studied for the qualitative study, Aguamarina, does not appear in this figure, both because it doesn't have any FONDEF projects in the mining sector (they have used both private funding and other public instruments), and because it is too new to appear in our data. Still, without Aguamarina, and even without Codelco and Universidad de Chile, there would be a network of biotechnology projects. On the other hand, we have heard complaints about the results of university and in-firm research on biotechnology.

The network of "supplier development" (not knowledge-intensive) is even less of a network than the one related to "lack of research". Formed with data from 6 projects, there is only a single component that is a proper network, and the most remarkable fact is that an association is present, possibly bringing together the many actors that form that cluster. But there are doubts that this network is representative of what has been happening regarding "supplier development". The company that is the undisputed leader in this is BHP-Billiton, with a supplier development program that has been highlighted by many of our interviewees.

[22] Codelco has a spinoff called "Biosigma", that received FONDEF funding , but works in isolation. In fact, this

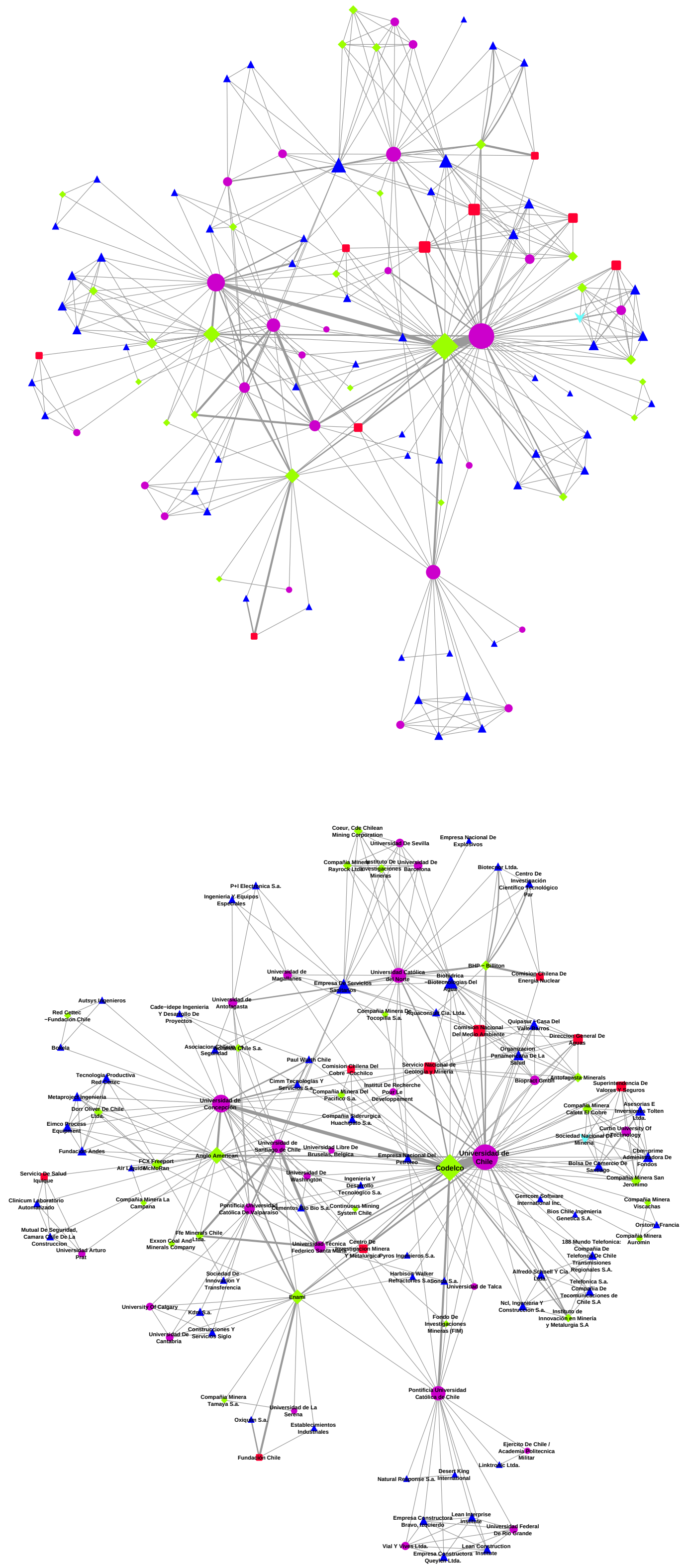

Figure 41: **Alternatives associated to economic problems**

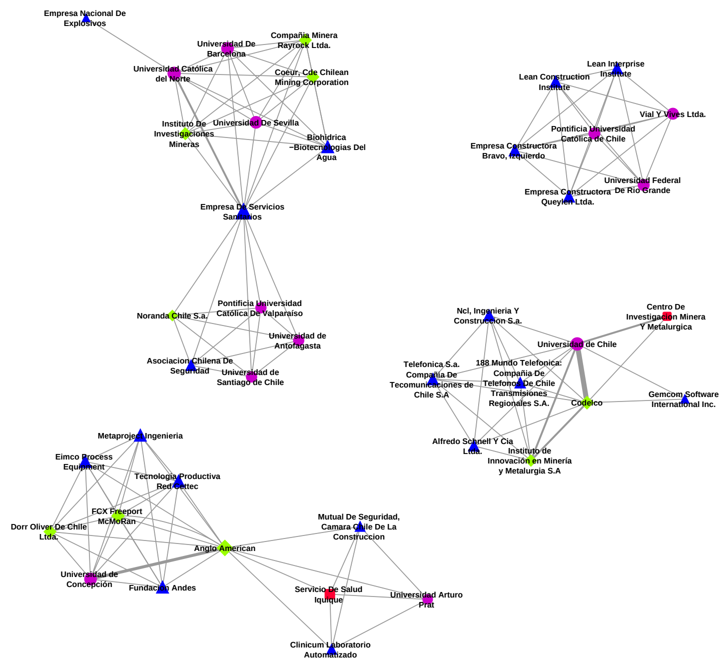

Figure 42: **Lack of research**

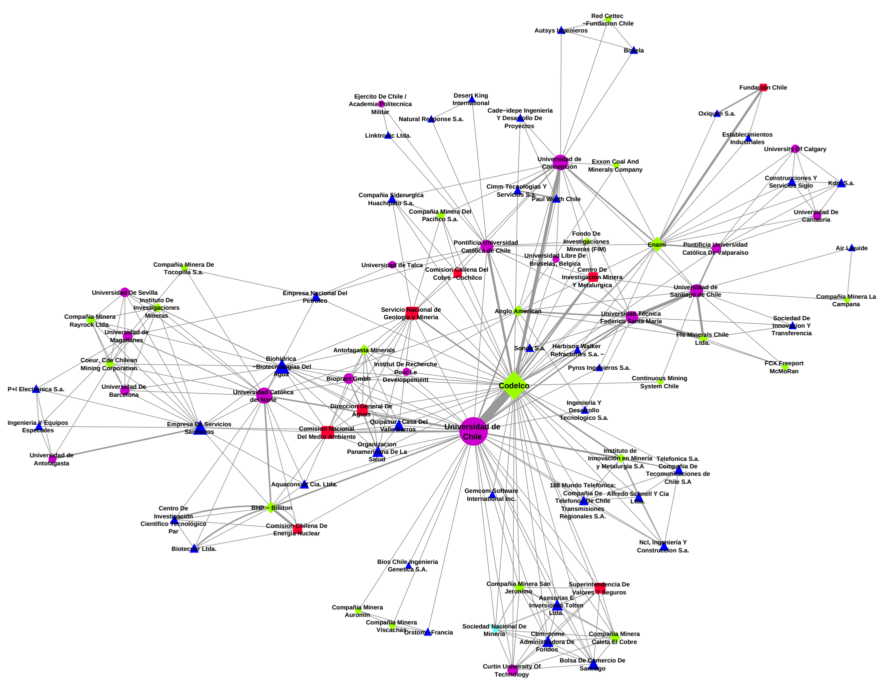

Figure 43: **Knowledge intensive suppliers**

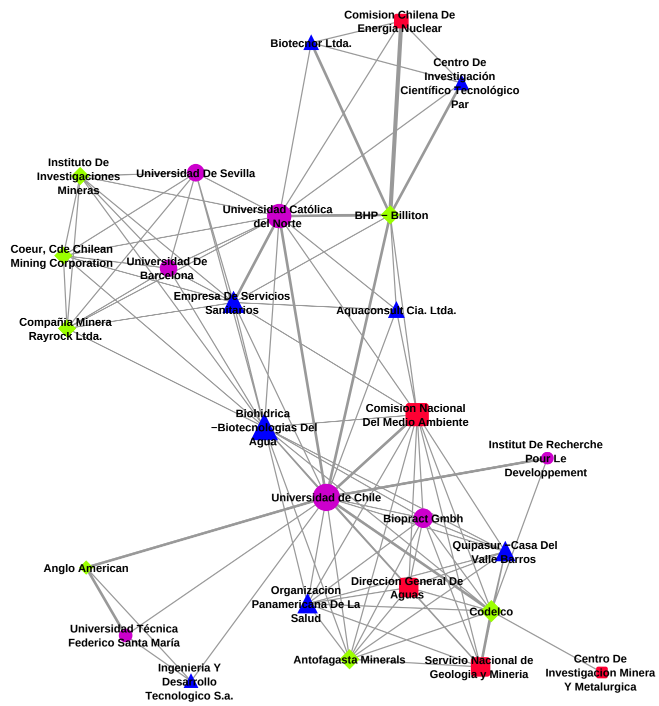

Figure 44: **Biotechnology**

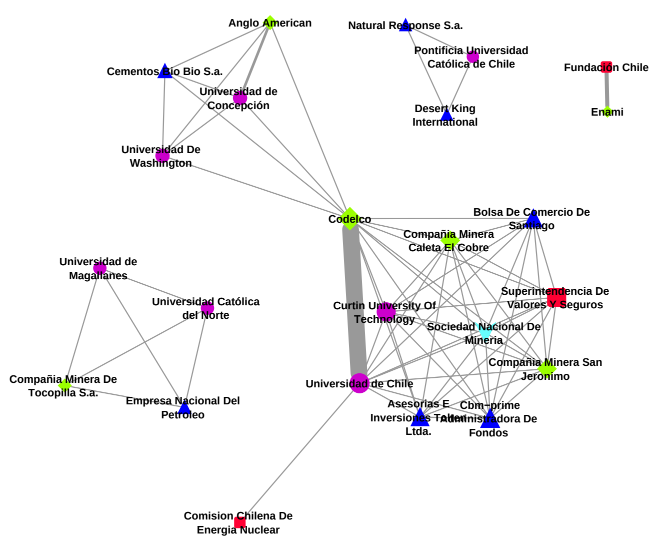

Figure 45: **Supplier development**

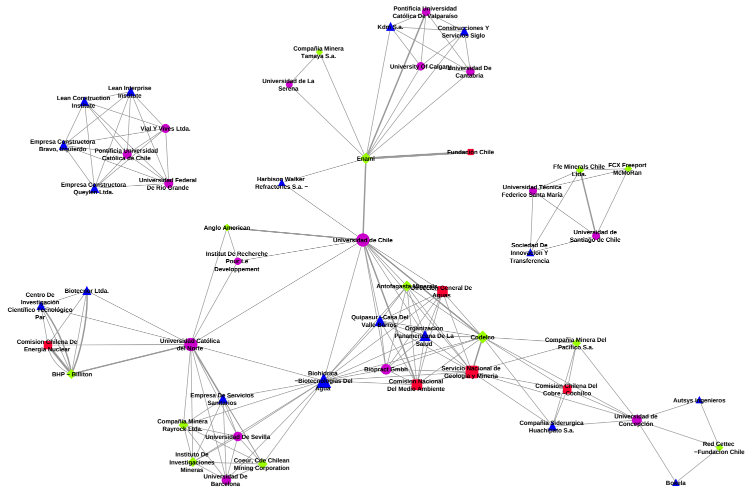

Figure 46: **Connections across economic agents**

The network in Figure 46 is formed by 14 different projects. For being projects related to "connections across economic agents", the density of the network is quite low. The largest component is especially fragile , depending on Universidad de Chile and Biohidrica

The three projects that were classified as related to "alternative uses for copper" barely form a network. Fundacion Chile participates in two projects, given its objectives and methodologies, should be the key actor of this network.

But the small amount of projects is consistent with the fact that Chile has technological capabilities accumulated in the extraction of copper, but not in the development of copper-based manufactures (or any manufactures for that matter). Economic diversification could most likely stem from the mining process than from copper-based products.

company is known in the sector for the secrecy sorrounding its work and results.

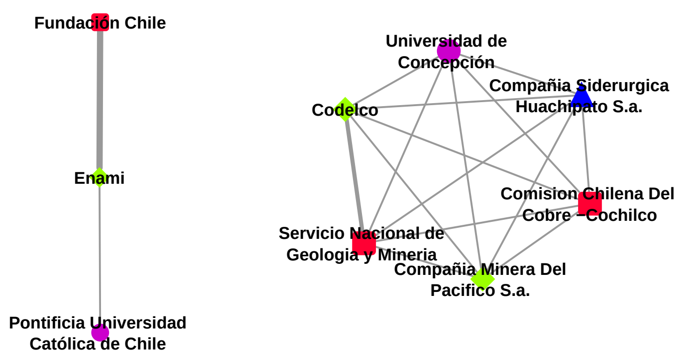

Figure 47: **Alternatives uses for copper**

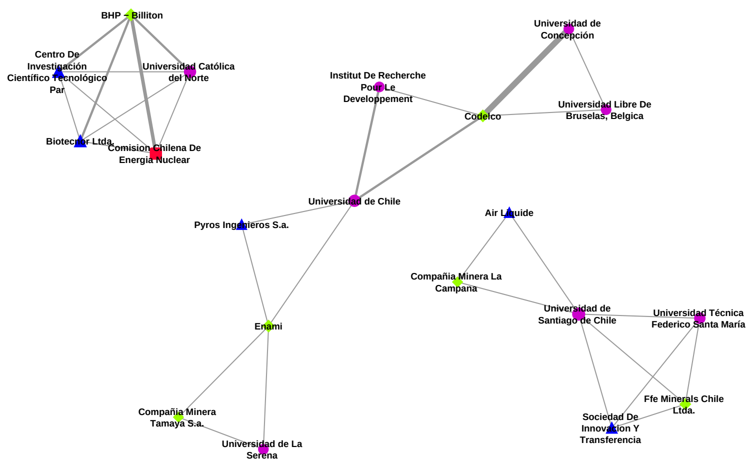

Figure 48: **Alternatives associated to productive problems**

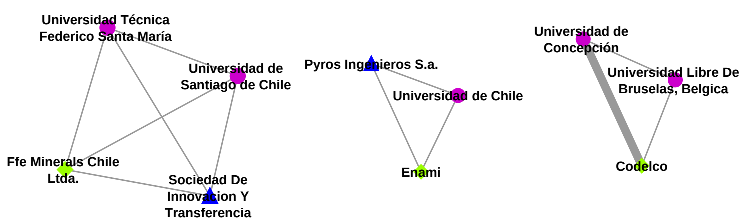

Figure 49: **Energy availability**

5.3.3 Productive problems

The whole network of path-repairing alternatives that tackle productive problems is formed by only 7 projects, 4 related to low ore grade and 3 to energy availability. The network has three separate components, the largest of which is connected by Codelco, ENAMI, and Universidad de Chile. Although it is a small sample of projects, what it appears in this network is that in productive problems, mining companies do not collaborate among them. One group has the two public comanies, not connected to each other. Another component has BHP-Billiton and Universidad Católica del Norte, and a third one has Minera Candelaria with Universidad de Santiago.Given the small size of the network, it is evident that its subnetworks should be similar. The network on decreasing ore grades shows several private mining companies, but in different network components.

Considering the importance of these two problems for the mining sector, it is quite likely that in this case FONDEF projects are not providing a good approximation to what has been done in terms of research. Although the lack of FONDEF projects in the area does show us something: research in this area is independent of public funding, and is not very collaborative. In other areas mining companies are participating in FONDEF projects. Here, they are not, maybe because they can fund their own research. Moreover, when they fund the projects they can have complete control over them, important because of the relevance these problems have for their production. An example of this is the work between Codelco and the Center for Mathematical Modelling at Universidad de Chile, where Codelco can have complete control over the projects.

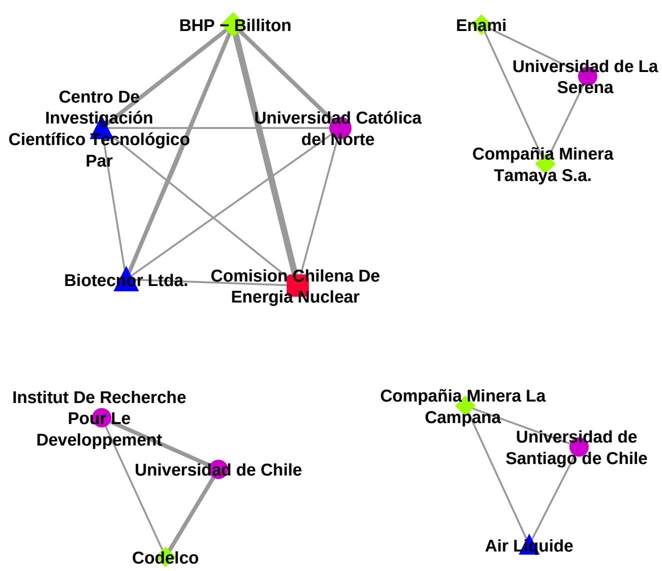

Figure 50: **Decreasing ore grades**

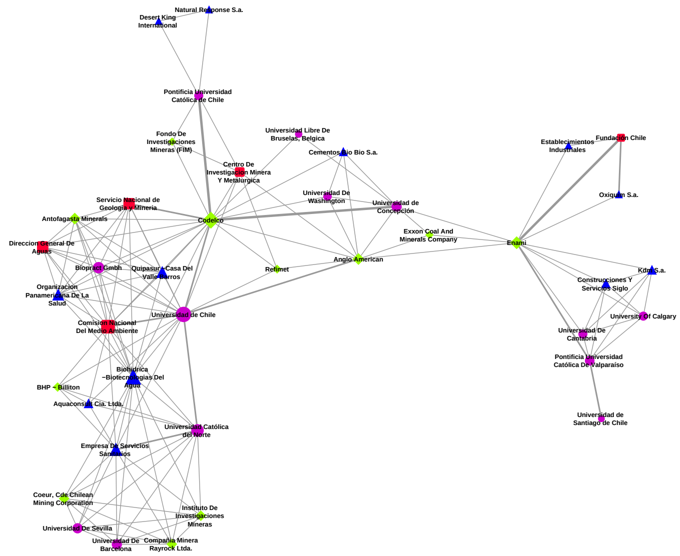

Figure 51: **Alternatives associated to environmental problems**

5.3.4 Environmental problems

A total of 16 projects are used to build these networks. For two of the problems studied, the recycling of materials and the use of salted or desalinated water, not enough information to build a network was found. Collaboration in projects that tackle environmental problems does form an interesting network. CONAMA, the national environmental agency, is one of the nodes with highest degrees, but its centrality is not very high. The most central actor in this network is ENAMI, followed by Codelco and Anglo American. Universidad de Chile is not as central as in other subjects, and Universidad Católica plays a very marginal role.

Compared to the network in productive problems, in environmental alternative pathways, with lower appropriability and high positive externalities -or rather the reduction of the current negative ones- much more collaboration seems to be occuring.

The network of air pollution projects (that has 5 projects) has three components, one with Universidad de Chile and BHP-Billiton, another with Universidad Católica and no mining companies, and a

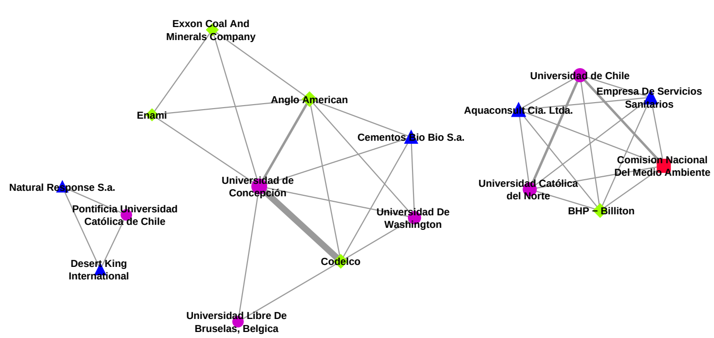

Figure 52: **Air pollution**

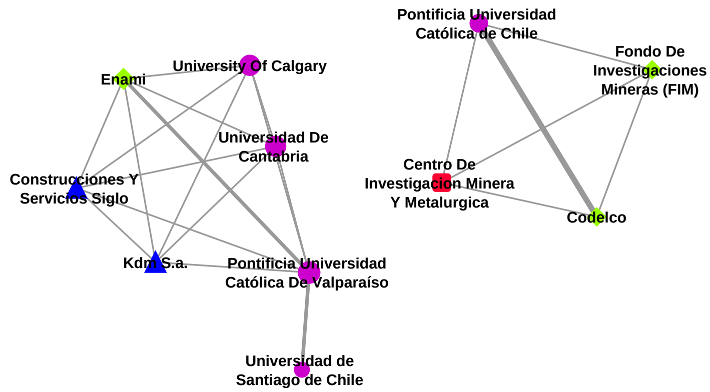

Figure 53: **Soil pollution**

third, larger component with several mining companies, led by Universidad de Concepción.

The soil pollution network (only 3 projects) has little participation of private mining companies[23], and is dominated by research institutions.

The water pollution network (7 projects) shows more interest of private companies in collaboration and research with public funding. There is also an important participation of public agencies related to mining, environment, and water, much more than for the other two forms of pollution. The high centrality of Biohidrica is remarkable.

Finally, there are four projects related to environmental problems that do not fit in the above categories. What is interesting about this is that there are things being done in terms of reducing the environmental problems associated to copper mining. Anglo American, that was important in many of the networks, has here a position very similar to that of Codelco.

5.3.5 Social problems

Finally, we will review networks associated to projects oriented at solving social problems. A total of 8 projects form the network of Figure 56. We then look at the subnetworks of "more or better employment" and "job safety". Projects associated to "improving quality of life" do not form a network.

The more important observation from this network is who are the central actors: Universidad Arturo Prat, Anglo American, and Universidad de Antofagasta. What is remarkable is that the Santiago-based actors that were important in most of the networks are only marginal here. Instead, two regional universities are the center of the network. This points in a clear direction: social problems are much more "regional", they affect directly the communities in the mining regions, and therefore it is regional universities that observe the problems and try to help the communities.

The two projects related to more or better employment barely form a network, which is a miniature scale version of the structure observed in many larger networks.

The five-project network associated with job safety has a very regional component formed mostly by regional organizations, close to the problems and "others"; and another component with several mining companies and two Santiago-based research institutions, that seems more disconnected to the local reality.

Even though there are relatively few projects oriented to social issues, we must come again to the "social license"-motivated collaboration hypothesis. If mining companies work with regional universities

[23]Fondo de Investigaciones Mineras is managed by CIMM, and funded by Codelco, Escondida, Zaldívar and Cerro Colorado.

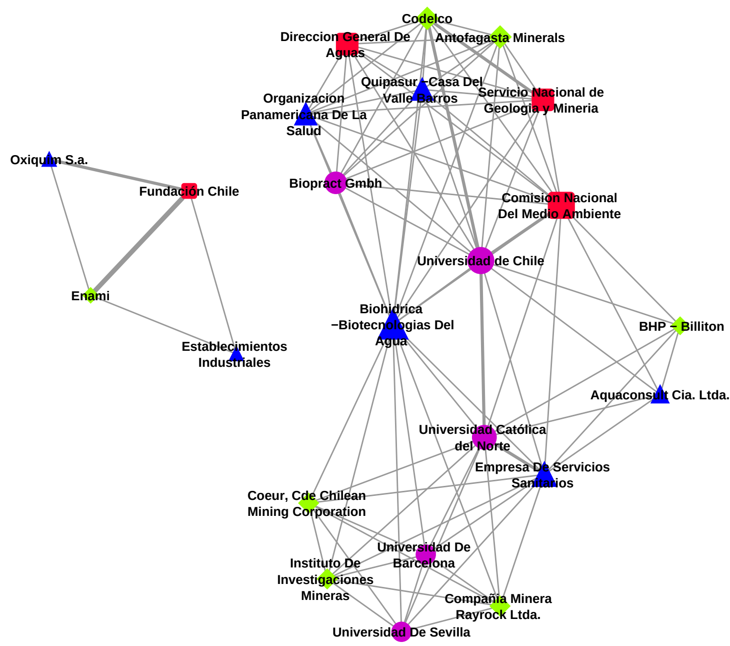

Figure 54: **Water pollution**

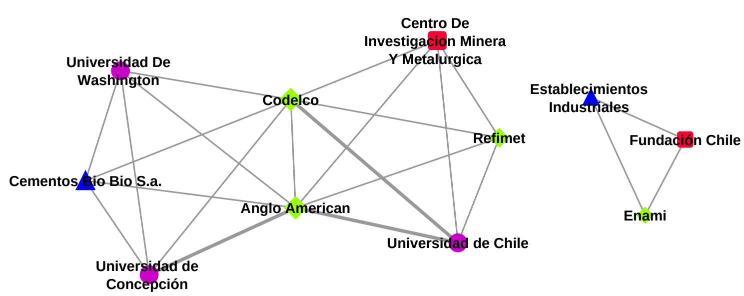

Figure 55: **Other environmental alternatives**

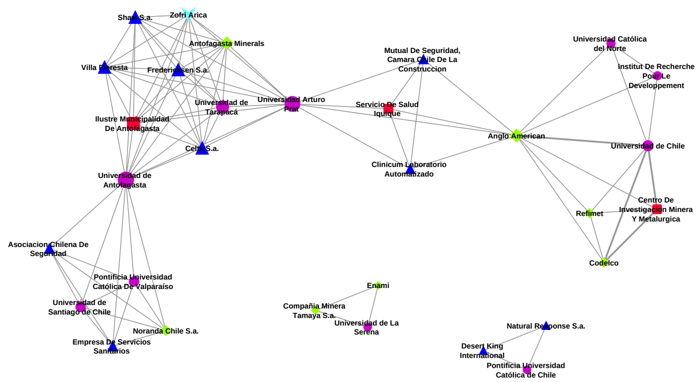

Figure 56: **Alternatives associated to social problems**

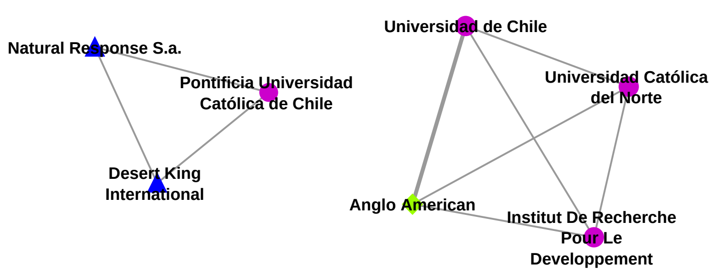

Figure 57: **More or better employment**

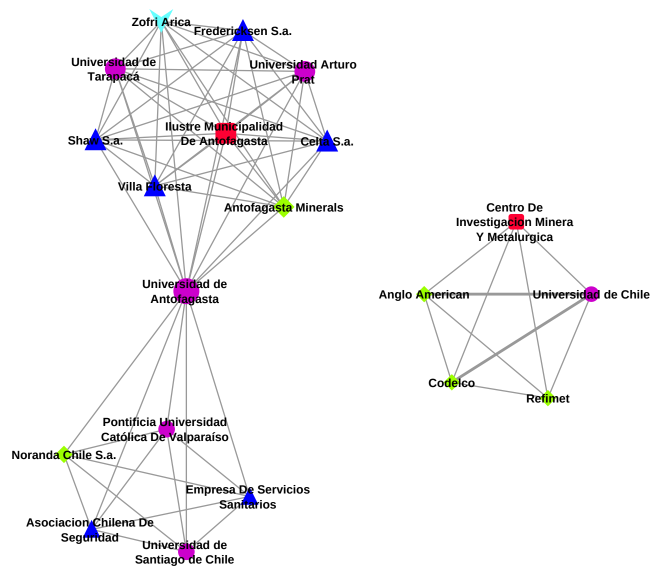

Figure 58: **Job safety**

as a way to improve their relationship with communities, many of the projects described in the previous categories would also have a "social" component, in terms of promoting the development of regional universities, instead of being purely motivated by R&D reasons.

6 Summary of findings and relationship with qualitative findings

For this report, the collaboration networks formed by participation in FONDEF projects were constructed and analyzed. Projects were classified according to the taxonomy of problems defined in the sectoral report, to contribute with this analysis to our understanding of the development of alternative pathways in natural resource based industries.

Although the database used covers only projects with public funding, and only a part of them, we do find some interesting patterns that are coherent with what we have found during our case studies. Our quantitative study is effectively complementing the work in the case studies, by providing an overall look at what is happening to solve the different problems we identified, not only in our case studies, but in the mining sector as a whole. In this final section we summarize the different sections and findings from this report, and connect these findings to those from our case studies.

General findings

A general description of the data -that regrettably could not be obtained for the last years- presents a bittersweet picture. The dominant trajectory is *not dominating* FONDEF projects, and there is no bias in the acceptance or rejection for funding against alternative pathways. Although there are many alternative projects in the “economic” category that are still in part dominant[24], even if we do not consider these, we find that there are a considerable amount of projects -and collaboration networks- trying to solve economic, productive, environmental, and social problems. However, the total number of projects is falling in the last years of our analysis, and the structure of the network of alternative projects might not be evolving in the best direction. The -maybe overly- optimistic interpretation is that projects are moving toward applied, firm-level innovation, and away from basic science. The negative one, that mining companies experimented at working with universities, and decided that in general it was not worth it, and now they mostly do research independently and oriented at their core-business (i.e. dominant trajectory) problems. Evidence from the case studies tilt the balance toward the negative interpretation.

One particularly worrying fall is that in projects associated to the development of “knowledge intensive suppliers”, a key part of a development strategy based on “path-creation” that stems from the experiences and capabilities accumulated in the mining sector.

The “water” concept is present along most of the analysis, but we missed projects associated to the use of sea or desalinated water. This is possibly because firms are working on this internally, with no interest in public funding, as observed in the case studies.

Comparing the different problem categories, economic alternatives have a defining characteristic: they are driven by “knowledge intensive suppliers” projectes, and about 40% of these do not depart from the dominant trajectory but develop technological capabilities along its lines, also consistently with what was observed in the cases. They are “path-creating” projects that could be important for long term growth and structural change, but are rooted deeply in the dominant regime. Projects in most of the other categories are much more “alternative”, but still correspond to our “path-repairing” category, as they never depart too much from the core of the dominant sociotechnical regime.

Keywords’ networks

We constructed networks with the keywords found in the projects to have a bird’s eye view of what is being done under each category.

Economic projects are clearly path-creating, with topics as biotechnology and automation playing signicant roles. But maybe the most important finding from the networks of keywords is that concepts such as collaboration and innovation barely appear. And rich collaborative relationships seem to be a key aspect in the success of the path-creating cases we studied.

Across environmental projects, the centrality of the “water” concept is relevant. But seawater and thickened tailings are missed. We know from the case studies that things are being done in these areas, but inside mining companies and with other kinds of public funds. This is consistent with things related to the core business being both more important and appropriable by firms, and therefore possible to develop in isolation. These will be developed independent of public funding or the universities’ research interests.

Collaboration networks overview

We looked at collaboration across mining companies, universities, public agencies, and other kinds of actors (mostly suppliers). We find a very interesting fact: “others” collaborate among themselves much more (around 40%) than mining companies do. Suppliers appear to be more interested in collaboration with equals than mining companies, that can do more things by themselves than what suppliers can, both because of a matter of resources and span across different sections of the productive process. Suppliers cannot protect a “niche” by themselves.

Another interesting and clear pattern is that collaboration moves away from suppliers and toward mining companies when we look at dominant vis-à-vis alternative projects (Suppliers are present in the

[24] The classification between “dominant regime” and “alternative” were not mutually exclusive. We found that there were many projects that were broadly along the lines of the dominant regime, but which had an important positive outcome in some of our four areas of sustainability problems.

same number as mining companies in the dominant network, but the former double the latter in the network of alternative projects). This is *absolutely consistent with the findings from the case studies*. It is a widely shared opinion that mining companies want to concentrate in their core business, and do “different” things only when they present a clear benefit in terms of increasing production levels, or reducing problems *without affecting* production. For alternatives, active participation of suppliers is a must, in the dominant trajectory instead, they are “simply” suppliers, without necessarily much to add besides getting their job done.

The government –through the participation of government agencies– appears to be more interested in alternative projects, something that makes perfect sense if these produce positive externalities (or reduce negative ones) and are not as appropriable as results from “dominant” projects. Another remarkable finding is that when we simulate Universidad de Chile out of the network, collaboration between mining companies falls *only for alternative projects*. Mining companies appear to need a push to work together in these projects, but when they want to work together to solve core-business problems, they will do it regardless of whether a highly-reputed university is asking them for participation or not.

Collaboration in alternative pathways

The evolution of the collaboration network in alternative projects has a clear pattern: the network starts timidly in 1991-1995, in 1996-2000 there is a full-fledged and relatively robust network, much less dependent one or two key actors (Universidad de Chile and Codelco), but this suffers a reversal in 2001-2005.

In general, universities are the most central actors, and mining companies tend to develop collaboration links with only a couple of institutions each. This is reasonable and positive, as trust and experience need to be developed in a collaborative relationship to improve results, and this is only possible if there is sustained work in time. The importance of several universities from the northern region of Chile is a very positive finding, considering how concentrated all kinds of resources are in Chile. However, this could be explained by two objectives that are far from research and innovation. Firms might collaborate with universities that are in the region where their mining operations are, both to improve their bonds to the community, and to approach future professionals and be recognized by them, in light of the current and expected shortage of professionals in the sector.

But the change in the network structure is puzzling. If it was driven only by the observed fall in the number of projects (from 32 to 23 from the second to third period of analysis), it is still important to understand *why* this fall took place. If the answer was that mining companies were losing interest in working with universities, this would be an important issue for public policy to look at[25].

Looking at particular actors, the experiment of deleting Universidad de Chile and its projects shows that more than 25% of the nodes would disappear, and the network would be less centralized. But it is impossible to know only with network diagrams the impact in terms of knowledge generation that the disappearance of a central actor could cause in the network (especially because of the path-dependence in knowledge accumulation). Anglo American, followed by Antofagasta Minerals, stand out as a private companies that seem to be relevant for FONDEF collaboration, although far behind Codelco. Some nodes that could have had more relevant roles are Fundacion Chile, that should be the key actor if “alternative uses for copper” was in fact an important network, and Universidad Católica de Chile (the largest research university together with Universidad de Chile), which has surprisingly few connections to mining companies.

Codelco deserves a special mention. Research on copper mining cannot get far without mining operations to learn about the problems and experiment with new ideas and technologies. In most of the networks studied, Codelco is by far the mining company with more projects and connections to a higher amount of other nodes. Connecting these results with some of our interviews, Codelco, or at least some people inside the company, might feel the urge for it to be an engine for the development

[25] There were important efforts to obtain updated data, that could have helped clear this issue out, but without positive results.

of R&D, the accumulation of technological capabilities, and in this way the improvement of national competitiveness in a knowledge based economy. Especially considering the relatively low R&D effort by most private mining companies. Adding the fact that in practical terms Codelco does not save money when obtaining public funding, the idea of helping the country develop technological capabilities seems like a reasonable explanation to the disproportionately large role played by Codelco in "alternative" FONDEF projects[26]. However, there are alternative explanations. For example, the high levels of collaboration observed between Codelco and universities could be attributed to Codelco's need to obtain its "social license to operate" at the national level and thinking on the long term, more than other companies. There are also conflicting versions on whether it is easier or more difficult for Codelco to spend money on technology development vis-à-vis private firms. Regarding its strong linkages with Universidad de Chile, informal contacts seem to contribute to them. But the observed fact is clear, Codelco is by far the company with more collaboration with universities.

Collaboration along the dominant trajectory

When looking at the evolution of networks of "dominant" projects, we find several interesting patterns. The first period is similarly small, possibly because of the recent arrival of private mining companies and the years without public funding. The second period, 1996-2000, shows –as for alternative projects– a relatively more robust network, but where Universidad de Concepción is the central actor. This is most likely related to the fact that this university is regarded as one of the best in the country in metallurgy. Mining companies are strongly present in this network, although suppliers are significantly less important than for alternative projects. In the third period there is an interesting development: the number of projects doesn't fall, but the number of nodes does. The average number of participants per project falls. Moreover, we saw that alternative projects fell significantly in number for the third period[27]. This is consistent with the negative interpretation that mining companies might be less interested in researching and collaborating for the development of alternative pathways, but have kept interest in improving the dominant trajectory.

When the complete dominant network for the 1991-2005 period is compared with the alternative one, an interesting difference is that the public sector is less central in the dominant network. This is consistent with more interest from the public sector in externality-rich alternative pathways. We also observe that together with Universidad de Concepción, Anglo American appears as one of the most central actors. This company increased its centrality with respect to alternative projects, but it must be noted that it was also relatively high in those networks.

Network theory

We also looked at some network theory indicators, particularly we explored whether these networks behave as the pervasive "scale-free" networks that have been described by complex networks researchers. The strongest finding is that they do not. However, when we look at the aggregation of the three different periods of the "alternative" projects networks, or at the network of dominant projects (which has less nodes), the distribution tends to approach the shape of the Pareto distribution that characterizes scale-free networks. While it is risky to say anything without more data, one possibility is that the network of dominant projects behaves in a more "natural" –according to the findings from complex networks researchers– way, and the network for alternatives projects does not, although it might tend to this as we aggregate more periods. The factors that could have been initially limiting network formation –such as luck of trust, knowledge asymmetries between actors, and other transaction costs– could be reduced as time goes by, but we do not have enough data to have any clear conclusion.

[26]Strictly speaking, we should evaluate the different network measures and adjust them according to the size of the different companies. But a preliminary observation shows that Codelco is overrepresented (besides its evident importance in absolute terms).

[27]Check footnote 21.

Collaboration in different problem categories

Finally, we looked at the networks for specific problem categories and sub-categories. Looking simply at the number of participants in projects in each category, projects related to social and environmental problems stand out with a higher average and median number of participants (around four) than projects in the economic category (less than three). This could be related to the appropriability of the results.

There are several findings in the networks of initiatives related to **economic** problems. Alternatives uses for copper don't seem to be an important field of development, as expected (the accumulated capabilities are in resource extraction, not manufacturing). The network of biotechnology-related initiatives is interesting, and differs from the rest in not being centralized in Codelco or Universidad de Chile. During the fieldwork, however, university research in this particular area was criticized as having no impact. The importance of Codelco is particularly evident in the network of knowledge-intensive initiatives, possibly for the reasons discussed before. An important negative finding is that knowledge-intensive initiatives are concentrated in Santiago, and the central region, and northern universities are not playing a significant role here, as they do in most other networks. This centralism was criticized by some interviewees, who stated that being close to the actual problems is key for success in innovative developments. It is important to remember, however, that other funding lines might be more appropriate to analyse path-creating projects.

The network of alternatives for **productive** problems is made of only a handful of projects, so not much can be said. If anything, it shows that mining companies do not collaborate among them to solve these problems. Considering the utmost importance of these issues, we consider that FONDEF projects are not really showing what happens in this respect, as mining companies will work on them regardless of public incentives (and they would also prefer having complete control over these projects).

Among **environmental** problems, for some categories we could not even build networks, and several projects did not fall into the categories we had defined. In sum, things are being done to tackle environmental problems, but maybe some of the most important ones are not observable in FONDEF projects, as they are closely related to firms' productive problems (i.e. water shortage), and are therefore the object of intra-firm development efforts. Other, non-core environmental problems are likely to be worked on through FONDEF projects, where results are less appropriable by firms. In fact, the network for environmental problems is much larger than the one for productive problems. However, the number of projects is still very small, and the lack of persistence in time is also worrying.

Finally, the networks of alternative projects directly associated to **social** problems have a very interesting characteristic: in contrast with all other networks, here it is regional universities that are the most central actors. With social problems close to the mining regions' communities, it is regional actors that can see the problems, understand them, and work on their solutions. This is also consistent with the idea that mining companies might work together with universities at least in part to improve their relationship with communities. Nevertheless, the number of projects classified as improving social outcomes is very small, confirming the lack of alternatives in this direction, as discussed in the final report of the copper mining in Chile study.