JACOPO SECCATORE

Gestão Sustentável de Recursos e Reservas para Mineração a Pequena Escala

Tese apresentada à Escola Politécnica da Universidade de São Paulo para obtenção do titulo de Doutor em Engenharia Mineral

Orientador: Prof. Dr. Giorgio De Tomi

São Paulo

(2014)

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Sustainable Management of resources and reserves in Small-Scale Mining

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It is clear that the conflict related to artisanal mining activities is not between humanity and nature but between humans at the bottom of society's hierarchy versus those on higher levels

(Marcello Veiga)

…y sobre todo, sean siempre capaces de sentir en lo más hondo cualquier injusticia cometida contra cualquiera en cualquier parte del mundo. Es la cualidad más linda de un revolucionario

(Ernesto Guevara)

Scientists dream about doing great things. Engineers do them

(James A. Michener)

RESUMO

Um dos maiores desafios para a mineração no Novo Milênio é a integração da Pequena Mineração no sistema ativo e sustentável de exploração dos recursos minerais. A Pequena Mineração (PM) é uma atividade de mineração definida por baixas despesas e receitas de capital e baixa produtividade. A Mineração Artesanal (MA) é apenas um subconjunto de PM, caracterizada pela mecanização rudimentar, recuperação ineficiente, condições operacionais inseguras e exploração do trabalho.

Essa tese pretende demonstrar as seguintes questões de pesquisa:

1) A PM pode ser sustentável?
2) Se sim, como pode ser avaliada?
3) Como a PM sustentável pode ser conseguida na prática?

Ao longo da tese é mostrado como a PM pode ser sustentável só saindo da dimensão artesanal. Tal processo depende da sua própria capacidade para operar de forma eficiente. Quando a eficiência operacional é alcançada, a sustentabilidade vem como consequência. Através da eficiência operacional, uma operação de SSM sai da condição artesanal, torna-se sustentável e a sustentabilidade dos meios de subsistência e ambiente circundante é estritamente consequente. Esta tese aborda a questão da PM, de forma quantitativa e não qualitativa. Indicadores básicos são individualizados especificamente para medir as características peculiares de minas artesanais, que as diferenciam das minas industriais. O objetivo desses indicadores é a padronização da avaliação de mina artesanal em termos quantitativos, uma importante ferramenta de pesquisa que não era disponível até agora. A análise desses indicadores permite medir a sustentabilidade potencial de uma mina artesanal, bem como sua atualização ao longo da transformação em uma pequena unidade de mineração industrial. Propõe-se uma nova abordagem para a gestão dos recursos minerais e reservas especificamente para a mineração em pequena escala, a fim de atualizar as minas artesanais em pequenas minas industriais. A abordagem proposta para o cálculo dessa reserva contém dois conceitos principais: uma "reserva mínima" necessária para o início do projeto, e a "replicação" da operação. A metodologia proposta, aplicada a uma operação de mineração subterrânea de ouro real, mostrou que, no caso em análise, as reservas necessárias para viabilizar a operação de pequena escala são da ordem de grandeza de 1/1000 de que as necessárias para a mineração em grande escala.

Este trabalho mostra como uma forma responsável e sustentável de PM é possível e viável, ajudando o desenvolvimento econômico da região onde atua, e criando externalidades positivas, como educação, capacitação, cultura da eficiência e consciência ambiental.

ABSTRACT

One of the biggest challenges for Mining in the New Millennium is the integration of small-scale mining in the active and sustainable system of exploitation of mineral resources. Small-Scale Mining (SSM) is a mining activity defined by low productivity low capital expenditure and revenues. Artisanal Mining (AM) is just a subset of SSM, characterized by rudimentary mechanization, inefficient recovery, unsafe working conditions and labor exploitation.

This thesis intends to answer the following research questions:

1) Can SSM can be sustainable?
2) If so, how can it be evaluated as such?
3) How can sustainable SSM be put into practice?

Along the thesis is shown how SSM can be sustainable only coming out of the artisanal dimension. Such a process depends on its own ability to operate efficiently. When operational efficiency is achieved, sustainability comes as a consequence. Through operational efficiency, an operation of SSM comes out of the artisanal condition, it becomes sustainable, and sustainability of surrounding livelihood and environment is strictly consequent. This thesis approaches the issue of SSM in a quantitative and not qualitative way. Basic indicators are individuated specifically to measure the peculiar characteristics of artisanal mines, which differentiate the latter from industrial mines. The purpose of these indicators is the standardization of artisanal mine evaluation on a quantitative basis, an important yet currently unavailable research tool. The analysis of such indicators enables the potential sustainability of an underground artisanal mine to be measured, as well as its upgrade over time towards classification as an industrial small-scale mining unit. It is proposed a new approach for the management of mineral resources and reserves specifically for small-scale mining, in order to upgrade artisanal mines into small-scale industrial mines. The proposed approach to calculate this reserve contains two main concepts: a “minimum reserve” required for the project start-up and “replication” to confirm the feasibility of continued operation. The proposed methodology, applied to an actual underground gold mining operation, proved that, in the case analyzed, the reserves required for the small-scale operation are in the order of magnitude of 1/1000 of that required for large-scale mining, when both businesses possess the same level of feasibility.

This work shows how a responsible and sustainable form of SSM is possible, achievable and viable, helping the economical development of the area where it operates, and creating positive externalities such as education, capacity building, culture of efficiency and environmental awareness.

LIST OF FIGURES

LIST OF ABBREVIATION AND ACRONYMS

AN	Ammonium Nitrate
ANFO	Ammonium Nitrate + Fuel Oil (Explosive)
AM	Artisanal mining
CAPEX	Capital Expenditure
CIMA	Compañía Industrial Minera Asociada
DNPM	Departamento Nacional de Produção Mineral
GPS	Global Positioning System
HDI	Human Development Index
INIGEMM	Instituto Nacional Geológico Minero Metalúrgico del Ecuador
JORC	Joint Ore Reserves Committee
NGL	Nitroglycerin
NGO	Non-governmental organization
OHS	Operational Health and Safety
OPEX	Operational Expenditure
PPE	Personal Protective Equipment
RD&I	Research, Development and Innovation
RMR	Rock Mass Rating
ROM	Run of mine
SADCO	South American Development Company (private mining company)
SSM	Small-scale Mining
UCS	Uniaxial Compressive Strength
UN	United Nations
UNECA	Unit of gold Extraction and Controlled Amalgamation
UNIDO	United Nations Industrial Development Organization
UPS	Universal Polar Stereographic coordinates
USP	Universidade de São Paulo
UTM	Universal Transverse Mercator coordinates
VOD	Velocity of Detonation

Note: this list does not contain symbols used in equations and mathematical expressions, which are explained in the text above each formula.

CONTENT

INTRODUCTION

This thesis assesses the issues of the sustainable management of small-scale mining (SSM). In particular, who writes intends to answer the following research questions:

1) Can SSM can be sustainable?
2) If so, how?
3) How can this be put into practice?

To answer these questions, this work is divided in three parts:

1) Part 1 clarifies the definitions for SSM, contextualize it with global statistics, and investigates its possibility to be sustainable;
2) Part 2 proposes a list of indicators that assess the potential of SSM to be sustainable
3) Part 3 proposes a new methodology for a sustainable approach to resources and reserves in small-scale mining and discusses its put into practice in a pilot project being carried on in Ecuador.

A great amount of Part 1 and every content of Part 2 and 3 have been published in, or have been submitted to peer-reviewed journals. To keep coherence in the contents, Chapters 2, 4, 5 and 6 appear in their original form of research papers.

PART 1 – CAN SSM BE SUSTAINABLE?

1. CHAPTER 1 – LITERATURE REVIEW

1.1 Lexical definition

The expression unambiguously defined, in English, as "small-scale mining", in Portuguese can be translated either:

- mineração *a* pequena escala, or
- mineração *em* pequena escala, or
- mineração *de* pequena escala, or
- pequena mineração

This Ph.D. Thesis has been developed in a Brazilian research institution. For this reason a proper lexical definition of its content must be given in Portuguese as well. Who writes is not a Portuguese native speaker, and does not possess such refined lexical tools as to make a decision based on his own opinion about which is the correct translation for “small scale mining”. Querying informal sources amongst Portuguese speakers, opinions are equally divided. Since it is necessary to standardize the expression that will be used to address the discussion of this Thesis, it is necessarily a scientific approach, and the only tools available to establish this pattern are the authority of the source and statistics.

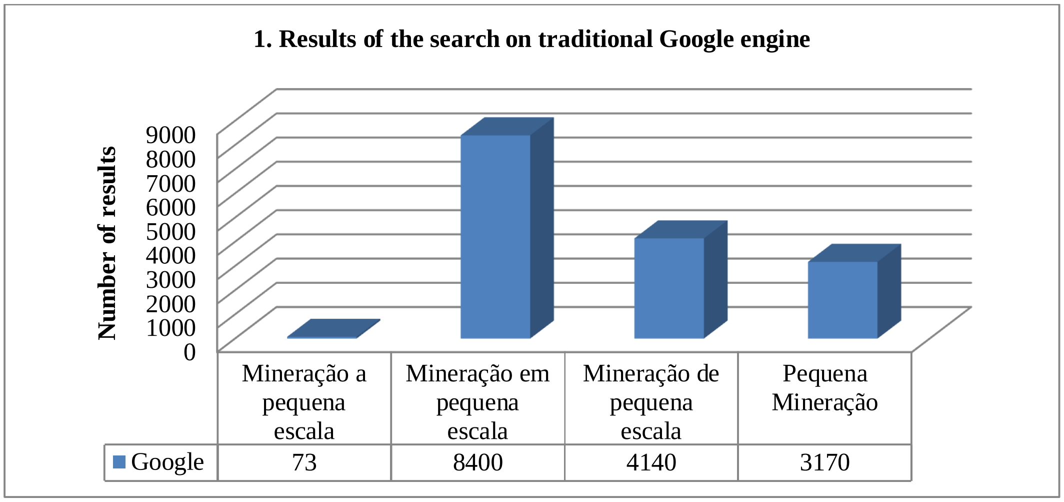
The graphs of *Figure **1*** show the results of the research among internet sources. Through the search engine Google and its academic engine Google Scholar were searched the four expressions, in "quotation marks" (a function that searches exactly for the words in the way that are contained between the quotation marks), under the following conditions:

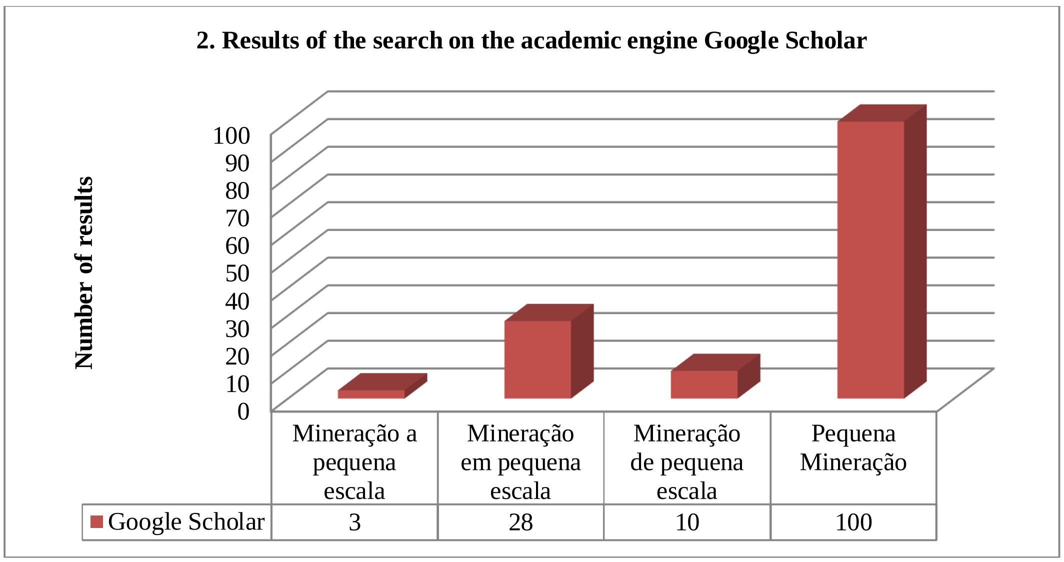
1. search on traditional Google engine
2. search on the academic engine Google Scholar
3. search on traditional Google engine, limiting the research to the sites with extension .gov.br (belonging to the Brazilian Government).

It can be noted that: results of search n.1 reflect the use of the terms in common language; results of search n.2 reflect the use of the terms in academic language; results of search n.3 reflect the use of the expressions in the language used by official agencies of the government of Brazil.

It appears clear that the official sources, both from the academic world and the government, are far away, in use, from the expression used in ordinary language. In governmental and academic sources, the term most recurrent is “Pequena Mineração”.

Based on the authority of the sources, as with a support by statistics, the expression “Pequena Mineração” will be used in Portuguese to translate “Small-Scale Mining”.





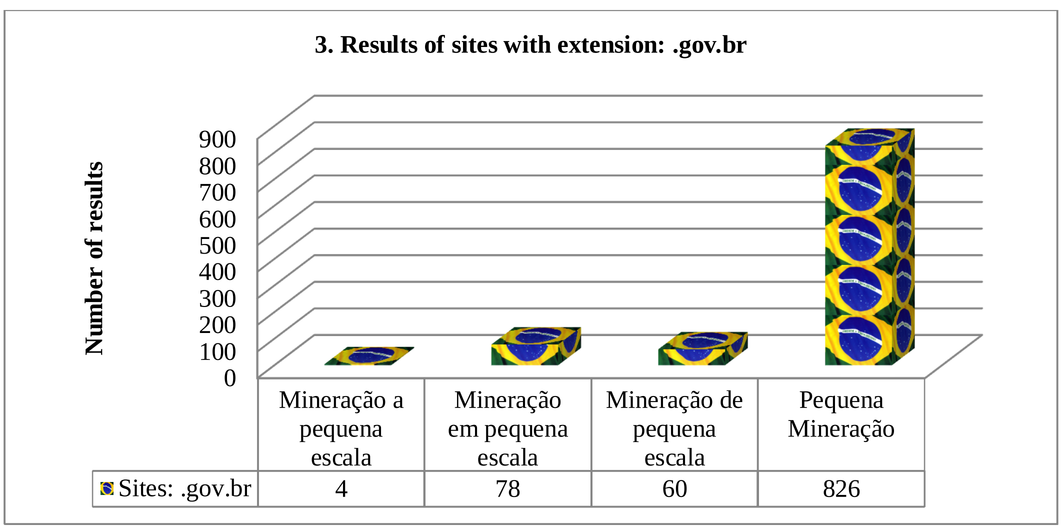


Figure 1 - Statistical analysis of the use, on the internet, of possible Portuguese translations for the English expression "Small-Scale Mining" (survey date: 28/09/2011)

1.2 Definitions

Approaching a discussion on the sustainable management of small-scale mining inevitably leads to deal with the abstraction of the concept of "sustainability" and the vagueness of the definition of "small-scale mining." Hence, the need to start with some definitions.

Definition of "Small-Scale Mining"

Often one refers to "Artisanal Mining" (AM) when talking about "mining by individuals, groups, families or cooperatives with minimal or no mechanization, often in the informal (illegal) sector of the market" (Hentschel et al., 2002). Nonetheless, a more precise definition is needed when dealing with the technical aspect of the problem. In 1972 the United Nations (UN) suggested the multi-attribute criteria for defining "Small-Scale Mining" (SSM): mine producing less than 50 000 t/y or 200 t/d, with capital investment below U.S. $ 1 million and annual sales less than U$ 1.5 million, manpower and up to 40 workers limited to 5 (five) years. In Brazil, mean values are applied by the National Mineral Research Department (DNPM): productivity between 10000 t/y and 100000 t/y is used a criterion to define a mining installation as a "small-scale" one. (CPRM, 2002). A similar definition is given in Ecuador for "Pequeña Minería" (Small-Scale Mining): productivity under 300 t/d for metallic ore or 800 t/d for non-metallic ore. These definitions are resumed in *Table **1***.

Table 1 - Summary of production and investment feature that define small scale mining

Source	*ROM [t/y]*	*Daily ROM [t/d]*	*CAPEX [$]*	*Revenues[$/y]*	*Human Resources*
ONU	< 50 $x10^3$	< 200	< 1 $x10^6$	< 1.5 $x10^6$	40
DNPM (Brazil)	10 $x10^3$ < ROM < 100 $x10^3$	-	-	-	-
Ley de Mineria (Ecuador)		< 300 (metallic ore) < 800 (non metallic ore)			

Other characterizing aspects of AM, as noted by Hilson (2002), are:

- mining in alluvial deposits near the surface;
- intense labor activity;
- remote and isolated location;
- rudimentary techniques and low technological knowledge;
- low degree of mechanization;
- low levels of environmental, health and safety awareness.

On the other side, as highlighted by Veiga (1997):

> The term small mining does not imply necessarily informal or rudimentary operations. There are many small mines in North and South America using adequate technologies to extract gold from small primary gold deposits respecting legal and environmental regulations.

Concluding from the above-mentioned definitions it is possible to come to a general definition:

> Small-Scale Mining (SSM) is a mining activity defined by low productivity (few hundreds of t/d ROM), low capital expenditure and revenues. Artisanal Mining (AM) can be defined as a subset of SSM, falling in the same range of productivity and investment, but that possesses as well the characteristics of rudimentary mechanization, inefficient recovery, unsafe working conditions and labor exploitation.

Definition of Sustainability

Sustainability is a very abstract matter. It is a concept with many definitions, according to many authors, and mainly depending on the reality being considered and the scale factor of this reality. The mainstream thinking of sustainability scholars visualizes the idea of three dimensions: environmental, social and economic sustainability. Depending on the visualization, these dimensions can be drawn, as shown in ***Figure 2***, as “pillars”(a), concentric (b) or overlapping circles (c) (Adams, 2006).

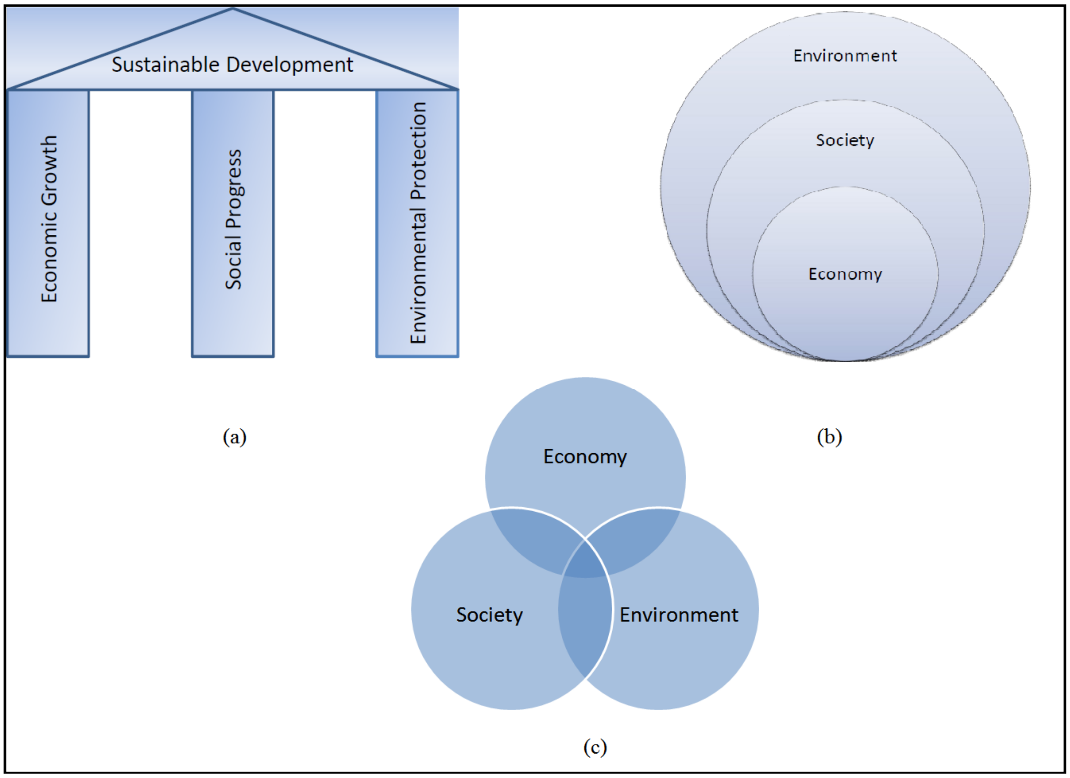


Figure 2 - Visualization of the main concepts of Sustainability (modified after Adams, 2006)

Anyway, in order to have a more precise definition of what sustainability is and by what criteria it is evaluated in our specific field, in this work sustainability will be limited to the definition of "sustainable mining". According to Vale (2002) the sustainability of mining depends on the spatial scale on which it is considered:

- International,
- National and
- Local

On an international scale sustainability must be considered on long-term, while at a local scale the short-term conversion of the stock of mineral resources in perpetual flow of net benefits is the critical key issue. The importance of the short-term conversion of mineral resources in net benefit is shared by Montero Peña (2002), who, in its study on the sustainability indicators for the extractive industry, highlights that "the exploitation of a reserve […] would be sustainable if it produces net gains related to fixed assets used in its exploitation". Almeida & Torrens (2002) define some criteria for a mining activity to be defined sustainable:

1. Improvement of mining;

2. Improving safety conditions in the mine;

3. Mitigation of environmental impact;

4. Using the right equipment for the conditions of each site;

5. Rational and comprehensive use of mineral resources and mineral community benefits;

6. Reduction of geo-environmental and geodynamic threats and hazards.

Concluding from the above-mentioned definitions, and the discussion of paragraphs above, it is possible to come to a general definition:

> “*Small-Scale Mining can be defined sustainable when it comes out of the artisanal dimension and can only be defined by the limits of its productivity*”

1.3 Statistics on Small-Scale Mining

Statistics of SSM in the world

In their "Global report on small–scale and artisanal mining" Hentschel et al. (2002) reported an estimate of workers involved in the activity of SSM. The authors highlight how "Despite (its) difficulties, there is no doubt that SSM is an important sector for employment generation." The numbers of this statistic are shown in ***Figure 3***, in the form of histograms.

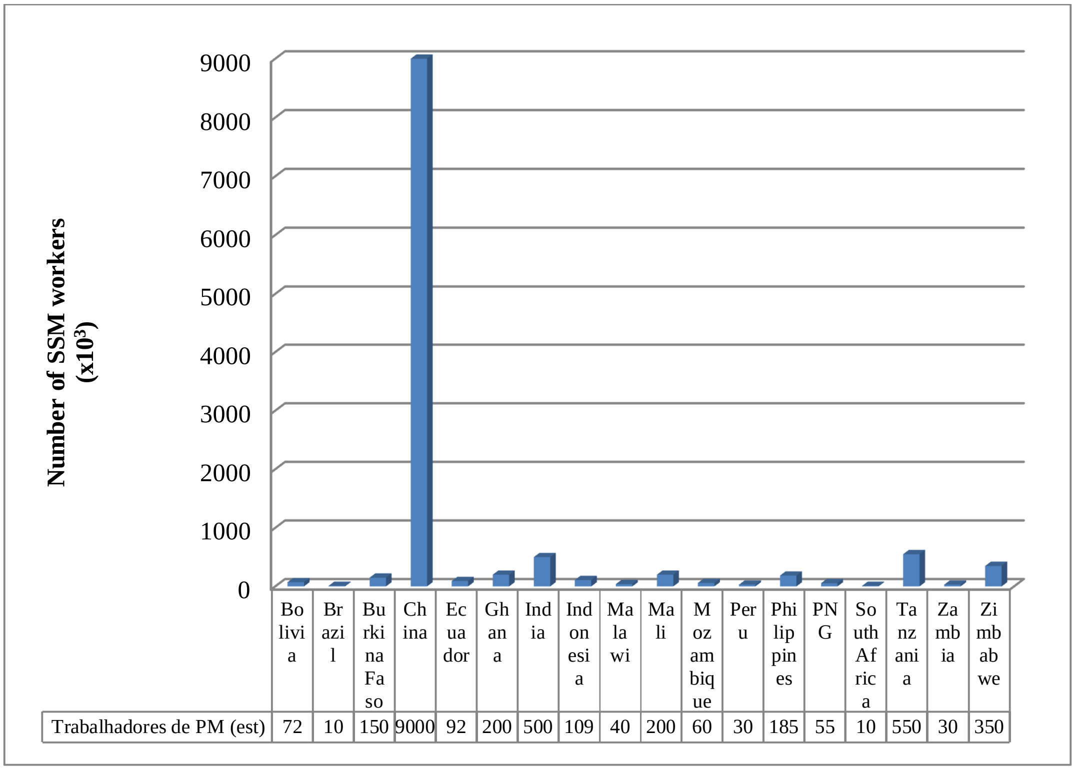


Figure 3 Estimation of SSM workers in the world
(Source of data: Hentschel et al.*, 2002)*

In a study on the sustainability of livelihoods related to the presence of SSM facilities, Hoadley & Limpitlaw (2004) compared similar data for number of SSM workers by country with indicators of quality of life, stressing that SSM provides a form of subsistence for the miners, but there is usually no direct generation of wealth. "The benefits provided by this activity are offset by the costs", such as low security and poor health conditions at work, or environmental degradation in a wider area around the facility. Based on the Human Development Index (whose calculation is explained in UNDP, 1990) and the proportion of people employed in SSM over the country's total population, Hoadley & Limpitlaw found a general trend of inverse proportionality between PM and employment conditions of well-being. This relationship is shown in the graph of *Figure **4***.

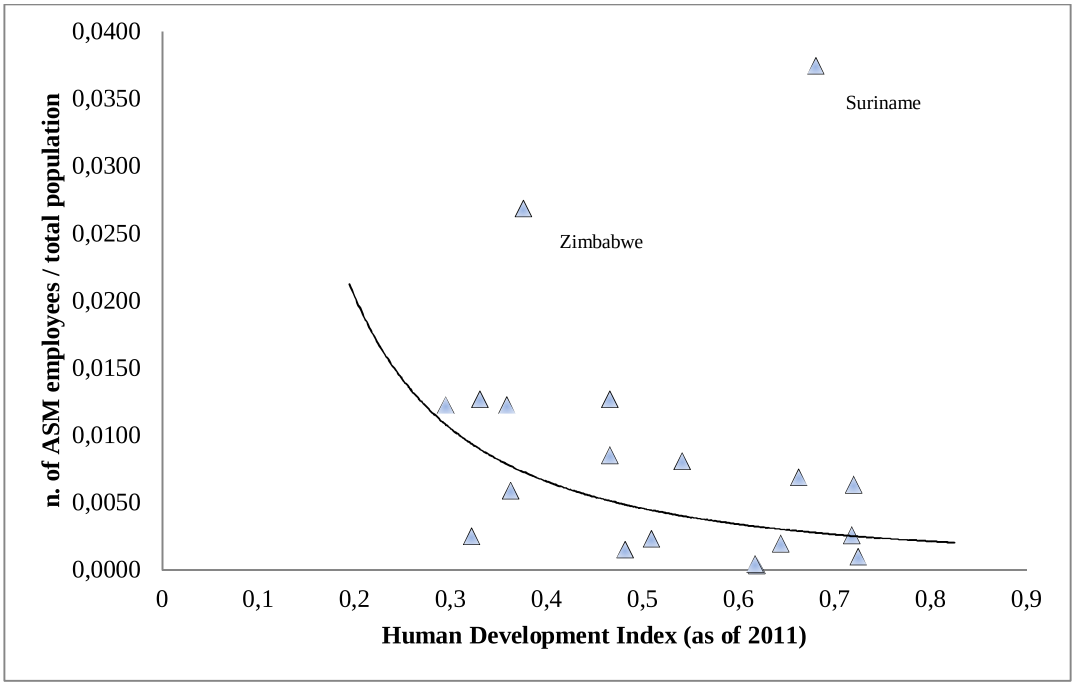


Figure 4 - Relationship between the Human Development Index (HDI) of a country and the proportions of its population involved in SSM (Source of data: Hoadley & Limpitlaw, 2004)

Looking at its technical aspect, Small-Scale Mining has a much faster response to market demand variations than any shift in productivity in large-scale installations. The easiness of installation, the low technological level and cost of equipment and the short-term of payback of the initial investment, often helped by the lack of bureaucratic authorization, create a rapid supply solution for the variations of the market demands. Bailey & Bernaudat (2010), with a graph from which *Figure **5*** has been adapted, have shown for the first how the trend of miners employed in AM follows on real-time the variation of price of gold on the market and the subsequent convenience of its production.

Figure 5 – Trends of gold price and number of Artisanal and Small-Scale Miners in the World (Projection after Bailey & Bernaudat, 2010)

Medium-scale and Small-scale mining are playing a bigger and bigger role in the world production of precious metals. Ericsson (2010) shows a general trend of reduction on the scale of the gold productivity, as shown in the graph of *Figure **6***. Always according to Ericsson's research, this global trend comes along with the ongoing lack of rich deposits and the general tendency to exploit deposits with a lower mineral grade, as shown in *Figure **7***.

It appears evident that SSM meets both rapid customization to the needs of the market and the technological and financial flexibility to adapt to lower size and grade of the deposits. These are all signs of a future development of SSM in precious metals, especially gold, in the coming decades.

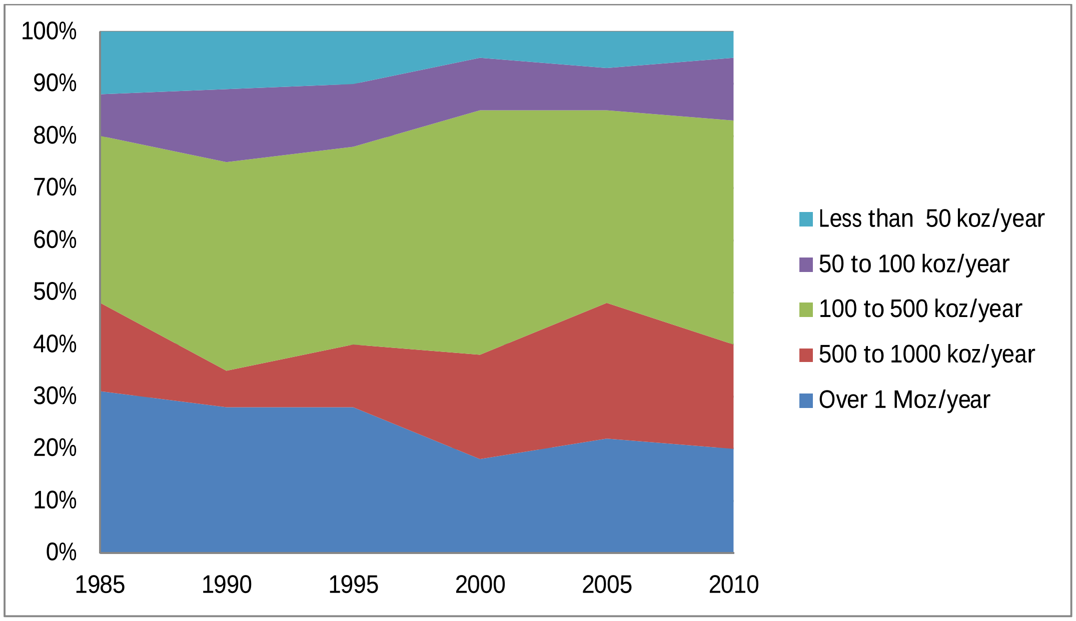


Figure 6 - Gold Production by mine size in the last 35 years

(Source of data: Ericsson, 2010)

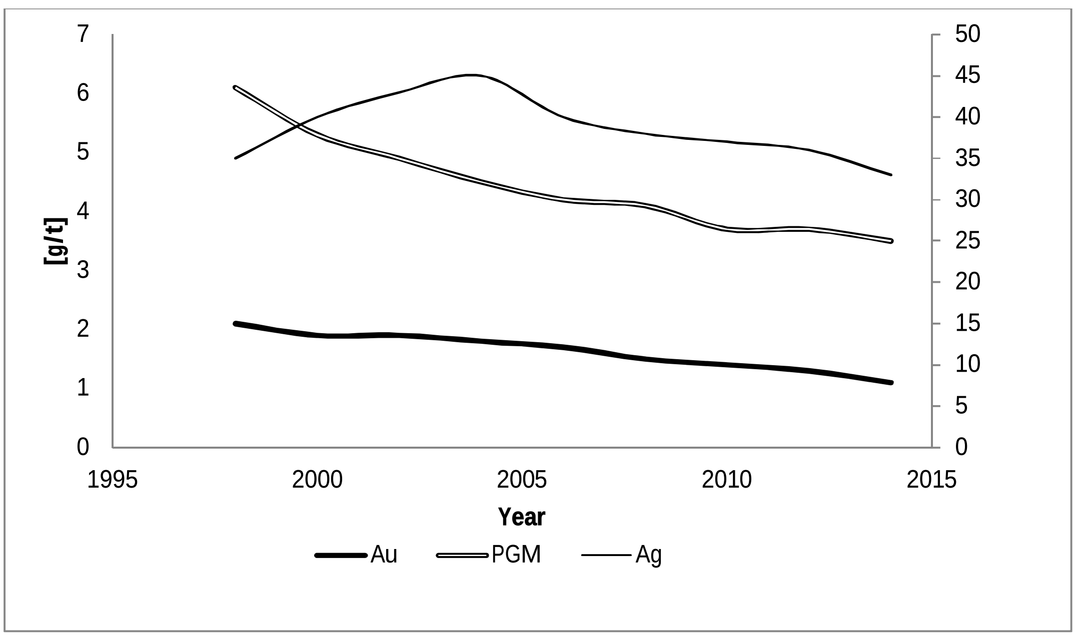


Figure 7 - Average grade of Gold, Platinum Group Metals and Silver in the deposits to be exploited (Source of data: Ericsson, 2010)

Statistics of SSM in Brazil

The National Department of Mineral Production (Departamento Nacional de Produção Mineral, DNPM) granted permits for "lavra garimpeira" (artisanal mining) in nine areas (32,000 km^2), most of them in the Amazon (5.6 million km^2), as depicted in *Figure **8***.

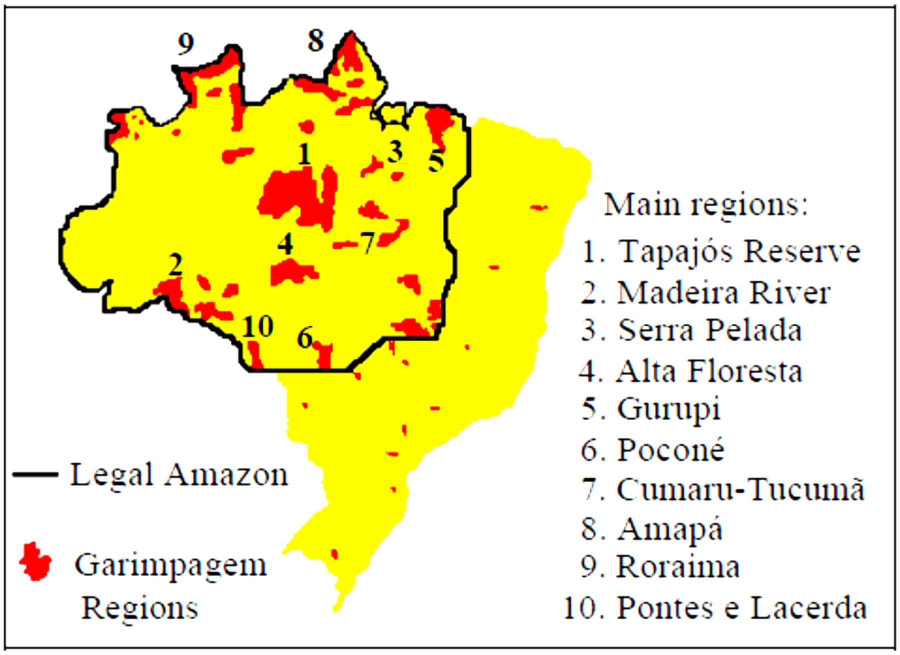


Figure 8 – Main areas of SSM in Brazil (Source: Veiga, 1997)

SSM holds in number the largest share of mining companies in Brazil, as reported in *Figure **9***. These data, part of an official report of the Brazilian Mining Institute, may have a bias in the census, being a part of AM informal and thus difficult to be registered. However, not all of the AM in Brazil is informal, and then the ratio should not be too different than shown below.

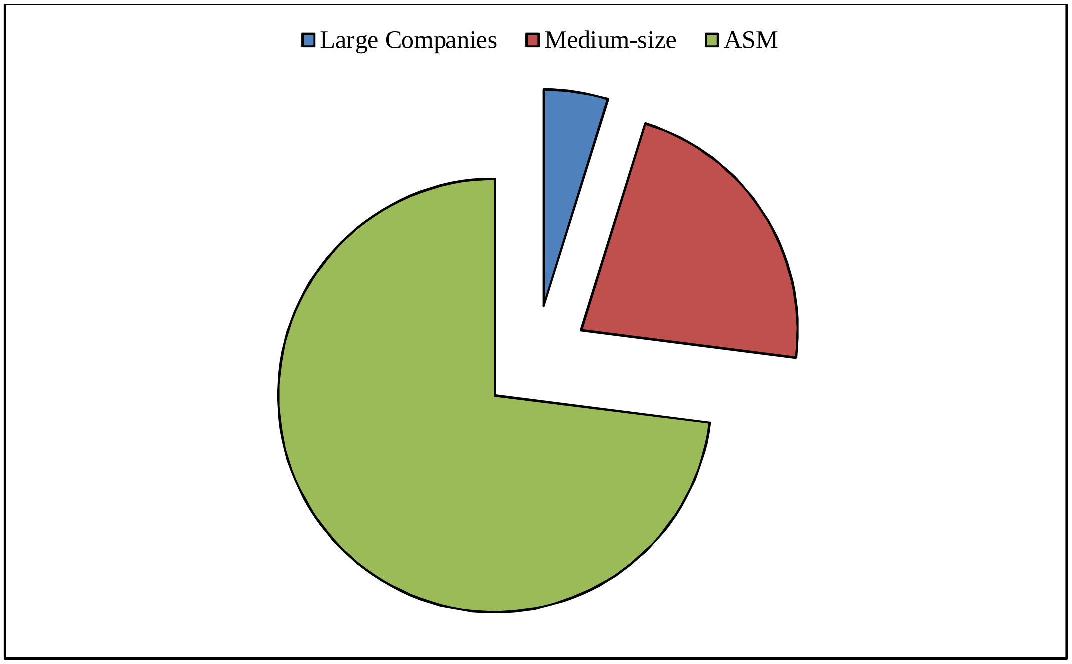


Figure 9 – Distribution of mining companies in Brazil, by size (Source of data: Vargas Penna, 2009)

According to Veiga (1997), the common criticism that "only the owners are getting rich with artisanal mining" is not quite true. In Brazil, partnership is the preferred working relationship, working in teams of about 6 people. The distribution of SSM by type of labor organization in the Amazon is shown in *Figure **10***. The “owner” usually divides with the workers 50% of profit net of operational costs.

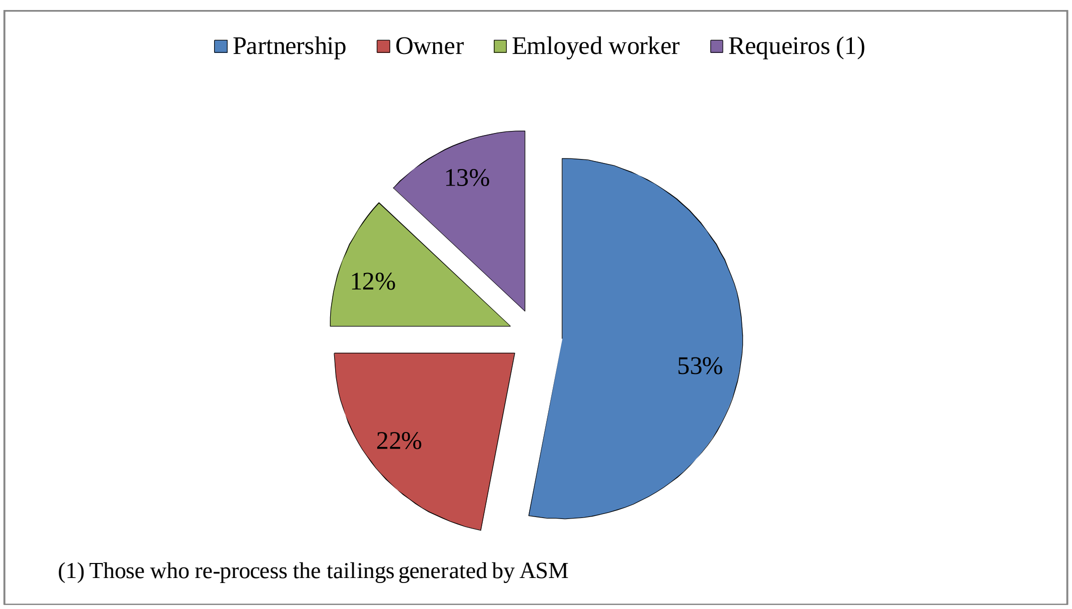
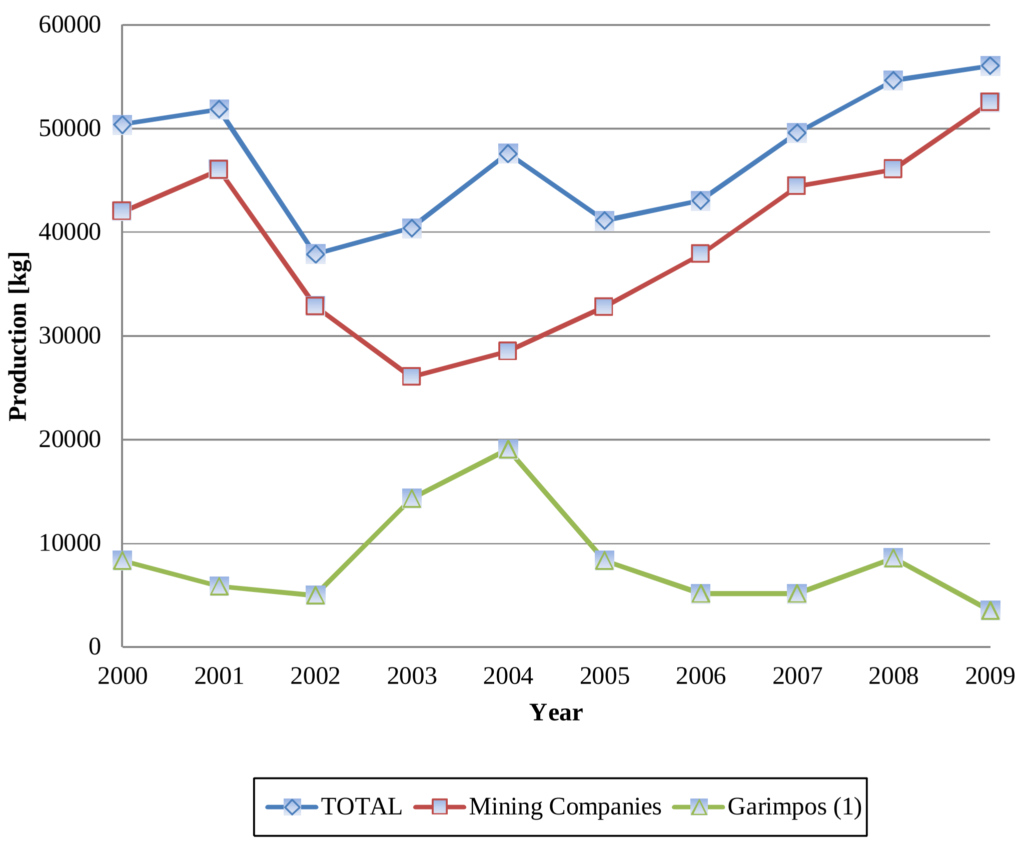


Figure 10 – Distribution of type of work organization in SSM and AM in the Brazilian Amazon (Source of data: Veiga, 1997).

Looking at the distribution of production between types of companies, the National Department of Mineral Research of Brazil (DNPM) annually publishes a summary of mineral products, containing information on domestic production and supply of mineral commodities. These data contain a distinction between production by official mining companies (with the authorization “Autorização de Lavra”) and the production of "garimpos" (artisanal mines with legal authorization of “Lavra garimpeira”). It should be noted that, when referring to the production of "garimpos", reference is made only to the portion of AM that pays Tax on Financial Transactions (Imposto sobre Operação Financeira, IOF) to the Brazilian government. Gold is the typical product of "mining" in Brazil. Data of gold production, by type of mining activity, are reported in *Figure **11***.



(1): Data about “Garimpos” production refers only to that part of ASM that paid Tax on Financial Operations (IOF) to the Brazilian Government

Figure 11 – Production of gold in Brazil by type of mining activity
(Source of data: DNPM, 2003, 2006, 2007, 2008, 2009, 2010)

It must be noted that the rapid increase in AM production between 2002 and 2004, resulting in the 2004 peak, corresponds to the negative trend of production of official mining companies between 2001 and 2003, resulting in the negative peak of 2003. Since data about AM possess some bias, deriving from Tax Declaration, part of these trends can be due to some legislative modification between 2001 and 2004. It is evident, anyway, that these production trends have nothing to do with some variations in Gold Price, that has been in a continuous positive trend since the beginning of the new millennium, as shown in *Figure **5***. Looking at total gold production in Brazil, it is clear that, after the low production of 2002, AM production in Brazil responded in a more rapid and effective way than the large mining companies. AM has supported the total production with a prompt production shift, till the moment in which mining companies recovered their delay.

1.4 Costs and benefits of small-scale mining to the present state

According to the "Global report on small-scale and artisanal mining" of Hentschel et al. (2002), small-scale mining has a number of costs and benefits in the technical aspects of geology and mining, the local aspects of the environment, society and micro-economics, and the overall aspect of the macro-economy. These costs and benefits are reported in *Table **2***.

The most obvious emphasis for this table is the total absence of benefits in terms of the environment data for AM to the present state. The current artisanal condition clearly generates more costs than benefits. However, properly developing the potential of AM to turn into sustainable SSM, the costs would be relieved, and the benefits would remain the same, and probably others would be generated, as discussed in the next paragraph.

Table 2 – Costs and Benefits of Artisanal Small-scale Mining (Adapted after Hentschel et al., 2002)

Aspect	Costs	Benefits
Geology and mining	- exploitation of a non-renewable resource − irrational working of high grade material − incomplete exploitation − processing methods − transport	+ possibility of exploiting smaller deposits + AM achieves successful prospecting without high cost + working of abandoned pillars, tailings etc. + small scale miners discover important deposits in remote areas
Environment	Environmental risks, emissions and damage to: − earth − soil − water (underground and surface) − air − flora and fauna − energy sources − ecosystems	
Society and Micro-economy	− precarious working conditions − negative health consequences (sickness, accidents) − infra-human living conditions − complicated dependency relations − child labour − unbalanced development between men and women − violation of resident and indigenous community rights − changes in the system of ethical values and it's consequences − insufficient social security	+ labour qualification + source of income (in money) + job creation
Macro-economy	Conflicts: · due to land and water usage · with governing bodies (judicial conflicts) · with large scale mining · with the indigenous population · with landscape protection objectives (national · parks, protected areas) − Smuggling – illegality (products & profit) − no tax generation − costs of controlling the sector − continuous costs resulting from social causes − uncontrolled development due to lack of planned exploitation	+ mobilization of natural resources + tax collection + active effect for the balance of payments + buffer for the labour market in cases of programs for structural adaptation + provides personnel reserves for large scale mining + contribution to regional economic development by: · cash circulation (social product) · investment · demand for products and services · mobility · structural consequences (alternative to agriculture) + avoids rural exodus + infrastructure development (road building, schools, energy supply) by small scale mining and neighbouring population + comparative financial advantages (products with a high labour coefficient in countries with high labour availability) + relative stable product supply even with market fluctuations + contributes to product diversity and export

1.5 Potential Benefits of a small sustainable mining

According to Hilson (2002), "It is important to clarify that, despite suffering its share of problems [...] small-scale mining plays a key role in reducing poverty in the developing world, and contributes significantly to national income and foreign exchanges. [...] These important contributions to socio-economic make small-scale mining activity and economic imperative".

Many of the installations of SSM in Brazil show signs of commitment and interest in technological innovation of processing techniques. What is lacking is the know-how and methodology to optimize the potential for exploitation. This know-howand its management methodologies, are the object of research universities and other entities for technical support. It is only through the approach of RD & I (Research, Development and Innovation) that the premises of the small mining with interest and potential for development by can become active and sustainable.

A UN Study on new business approach on small-scale mining (Chaparro Avila, 2003) confirms all this:

> It is not often recognized that the *garimpos* in Brazil are getting stronger and multiplying because of access to new technologies, such as pumps, crushers and mills. [...] This led to a new generation of miners: entrepreneurs who have the capital to buy and maintain the equipment. [...] One distinguishing feature of the formal, or controlled, operations, meaning those that conduct mining as a business activity with a defined structure as far as legal, accounting, technical, administrative and environmental matters are concerned, is that they are designed to continue in the same place for a long period of time, as they involve a high level of capital investment[...] Many of the controlled (formal) facilities use technologies that obtain higher profit levels by increasing productivity, reducing labor costs and conducting technical research; they also have procedures that are managed, designed and constructed in such a way as to minimize the environmental damage caused by the use of dangerous substances, and to minimize the release of hazardous solid residues throughout the treatment process.

Kilgerman et al. (2001), in an analysis of the activities of SSM, specifically in Brazil, concluded that: "small-scale mining presents favorable characteristics: flexibility, access, adaptable technology, low-cost, local tradition and opportunity for social mobility." The challenge is to take advantage of these favorable features by terms of technical know-how and RD&I approach, to improve the production process, optimize the operating assets, and help develop, consequently, the social and environmental parameters that depend on the economic success of the mining company.

1.6 A specific case: Small-scale gold mining

Small-scale gold mining in Brazil and South America

According to Veiga (1997), virtually all Latin American countries have artisanal mining activities, and gold is the most common commodity produced. Data for that study were obtained from field visits, contacts with National Departments of Mines, mining companies, international agencies, consulting firms involved in small-scale mining, interviewing individuals, news on the internet and some publications available in local newspapers and international technical journals. Veiga's study of small-scale mining in Latin America is the most extensive and detailed published so far. Even considering that Veiga's 1997 data are outdated, and that the dramatic increase in the price of gold of the last years has increased the value, it is expected that the proportion of the distribution of values among the Latin American countries has not varied. Data are reported in *Table **3***, and the proportions amongst them are reported in *Figure **12*** and *Figure **13***; *Figure **14*** reports the results of gold production per capita from artisanal miners.

Table 3 - Estimated gold production and number of miners in Latin America in 1997 (Source of data: Veiga, 1997)

Country	Gold [t] min	Gold [t] max	Miners, min	Miners, max
Brazil	30	50	200000	400000
Colombia	20	30	100000	200000
Peru	20	30	100000	200000
Ecuador	10	20	50000	80000
Venezuela	10	15	30000	40000
Suriname	5	10	15000	30000
Bolivia	5	7	10000	20000
Mexico	4	5	10000	15000
Chile	3	5	6000	10000
F.Guyana	2	4	5000	10000
Guyana	3	4	6000	10000
Nicaragua	1	2	3000	6000
Dominican R.	0,5	1	2000	3000
Others	2	5	6000	15000
TOTAL	**115,5**	**188**	**543000**	**1039000**

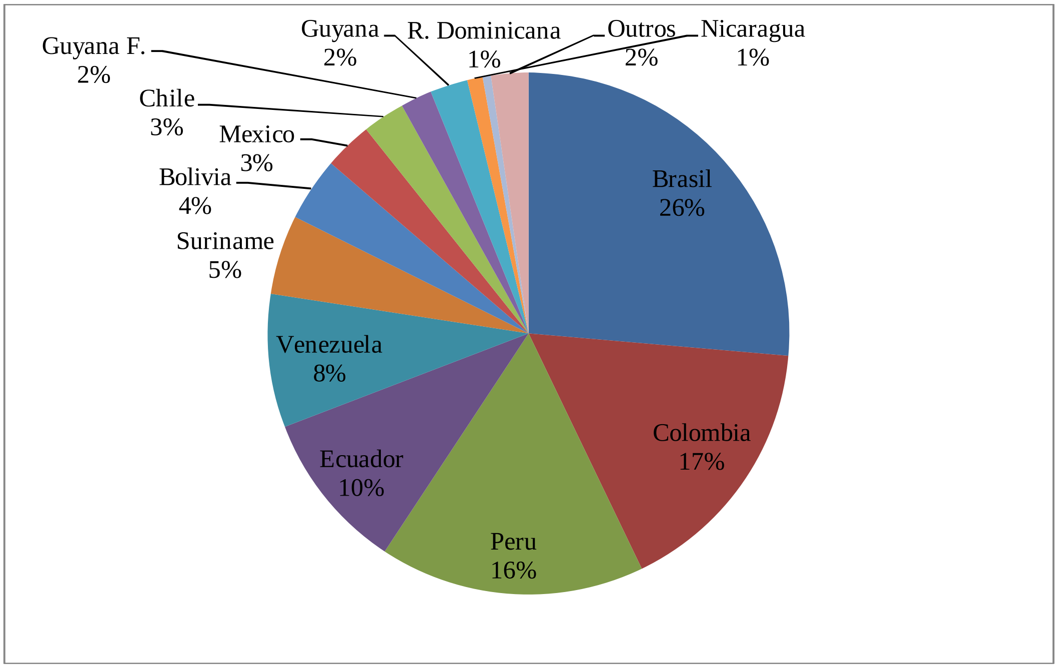


Figure 12 - Distribution of gold production of PM in Latin America in 1997 (source of data: Veiga, 1997)

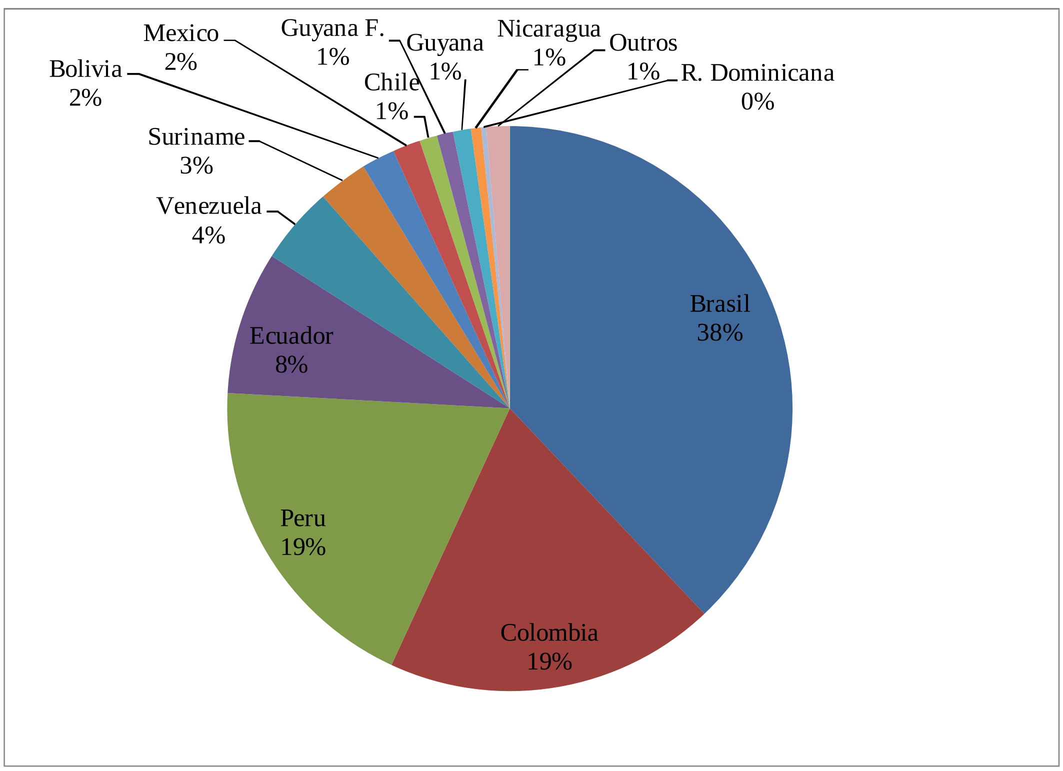


Figure 13 - Distribution of population of small-scale miners in Latin America in 1997 (source of data: Veiga, 1997)

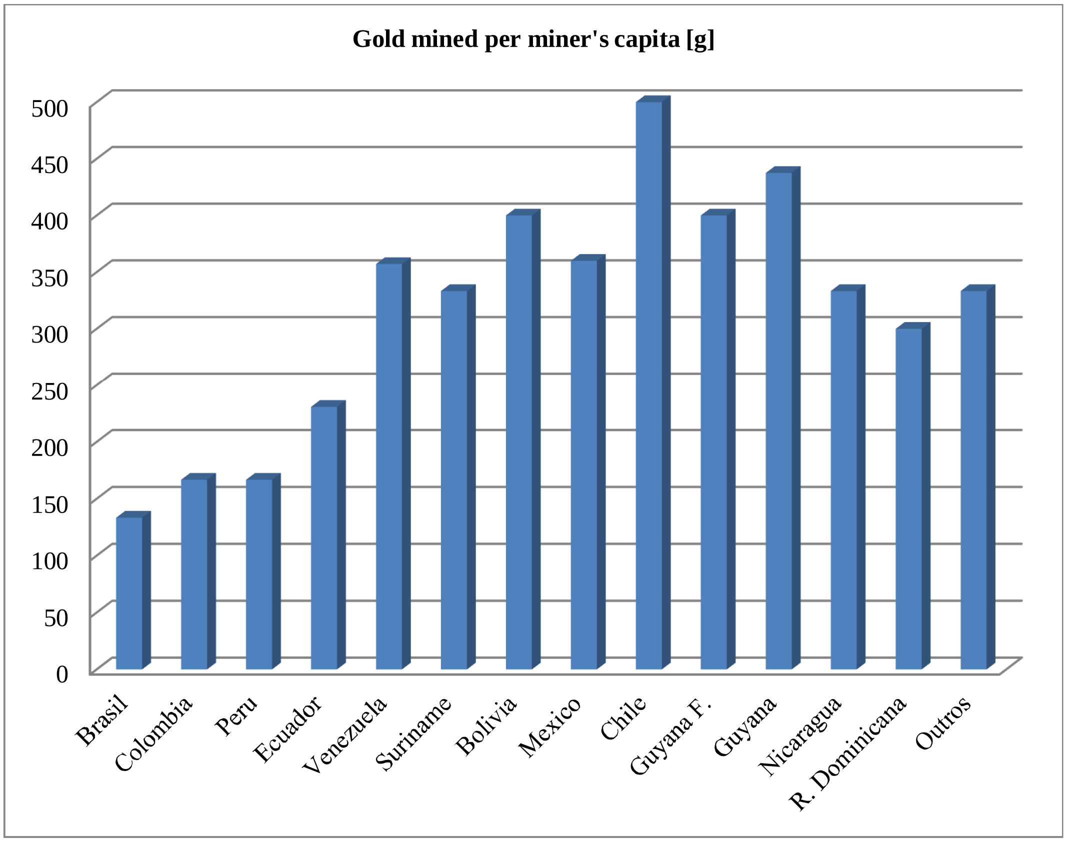


Figure 14 – Gold mined per artisanal miner's capita in Latin America in 1997 (source of data: Veiga, 1997)

Veiga noted that there is a certain correlation between gold production and number of miners. This correlation is represented in the graph of ***Figure 15***.

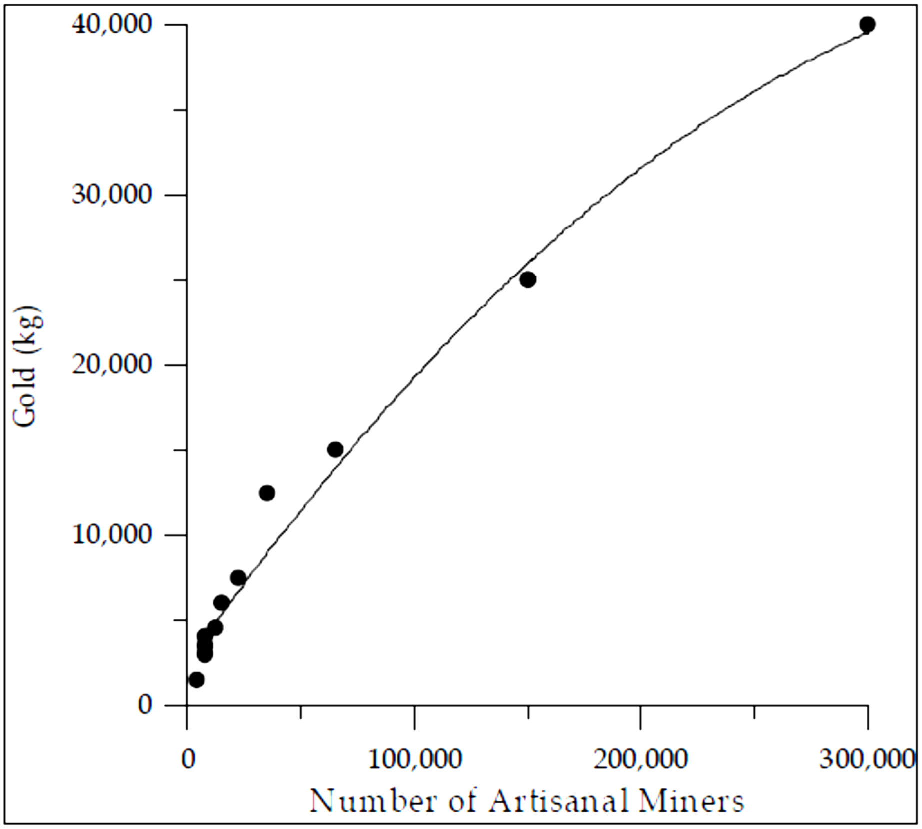


Figure 15 - Correlation between gold production and number of artisanal miners (Veiga, 1997)

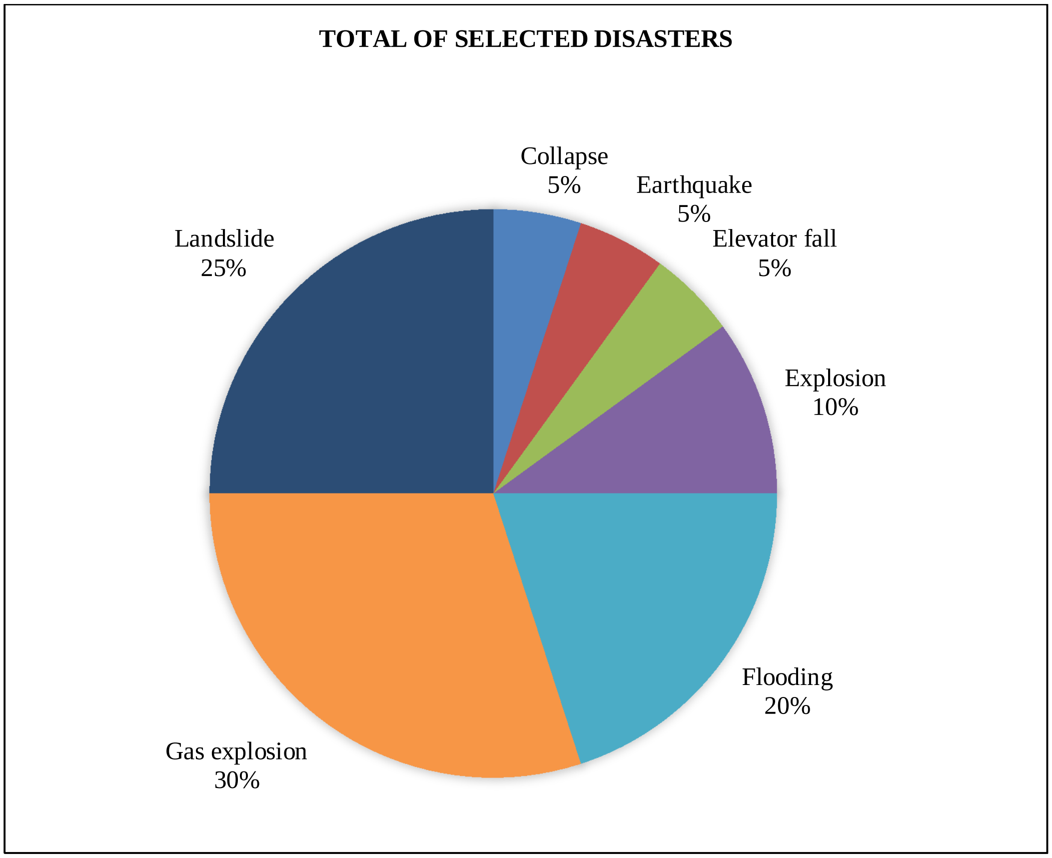
1.7 Accidents in artisanal mining

As discussed, Artisanal Mining is characterized by rudimentary mechanization, inefficient recovery, unsafe working conditions and labor exploitation. Due to these issues, accidents are very common in artisanal operations. Information on the subject, nonetheless, is very scarce, since accidents are often not investigated nor reported, and, when reported, media does not report sufficient technical details to determine properly the causes and effects of the event in terms of JS&H analysis.

The ILO Analysis (1999)

One of the first statistical studies in these terms has been described in the “Report for discussion at the Tripartite Meeting on Social and Labor Issues in Small-scale Mines by the International Labor Organization” (ILO, 1999). The study analyzed 21 selected disasters in artisanal mines between 1992 and 1998, occurred in Bolivia, China, Colombia, Niger, Nigeria, Peru, and United Republic of Tanzania. The accidents are associated to the cause of the event and to the consequences in terms of deaths occurred. Hereafter data from ILO are analyzed statistically to provide an overview of causes of accidents (***Figure 16***) and incidence of such causes on death occurrence (***Figure 17***). In China AM of coal is very diffuse (Hilson, 2006), and in the list of ILO accidents, all events occurred in China appear to be caused by gas explosion, a typical accident of coal mining due to the presence of firedamp (natural gas) and dispersed coal dust. Artisanal mining of coal is not diffused outside China. Therefore, to give the analysis a more proper significance, data are analyzed on two steps, first considering all the accidents and then considering only those occurred in non-coal mines

Geotechnical and hydrogeological causes appear to be the most influential in terms of cause of accidents and of death consequences. This is due to the large impact, in case of their occurrence, in terms of area or volume of influence: a geotechnical instability (landslide on open-pit or collapse of tunnel roof in underground environment) or a hydrogeological disaster (flooding) have a widespread impact over the mine layout, while isolated events like uncontrolled blasts or equipment failure have a punctual impact immediately around the area of occurrence.



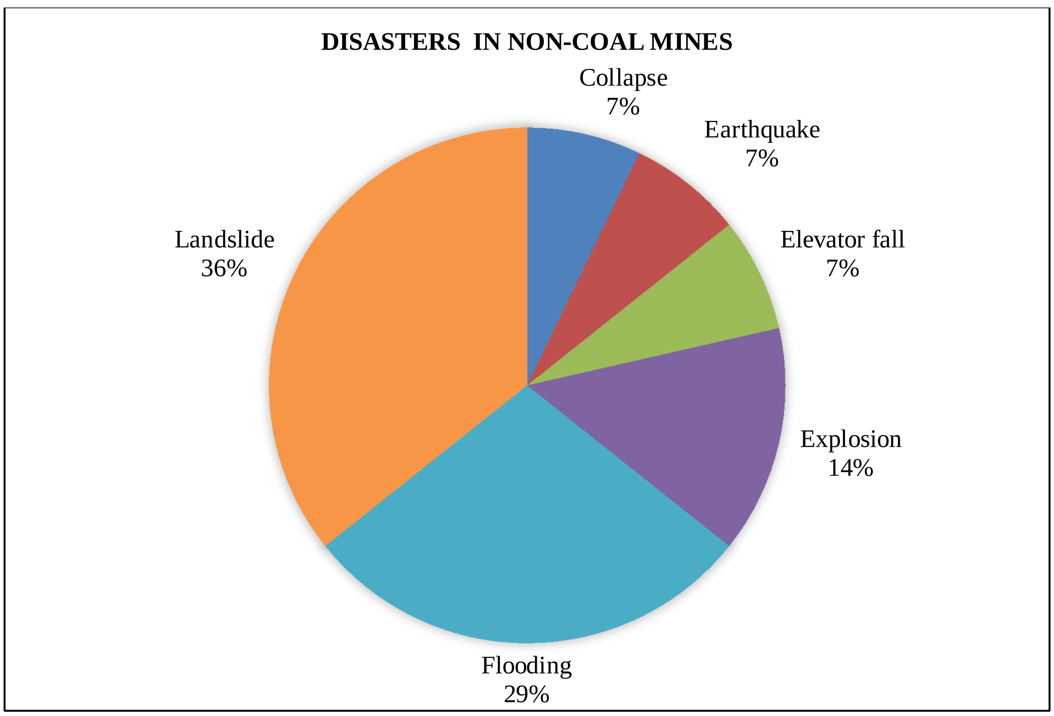
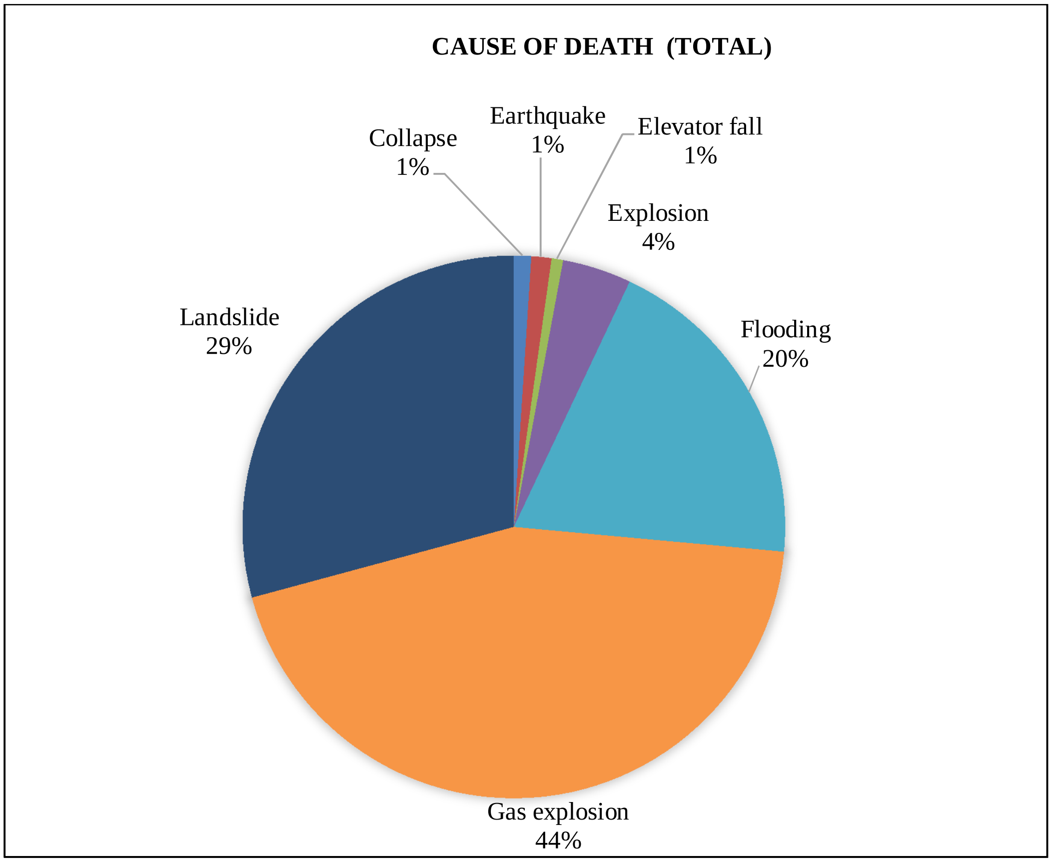


Figure 16 - Causes of selected AM disasters, 1992-98



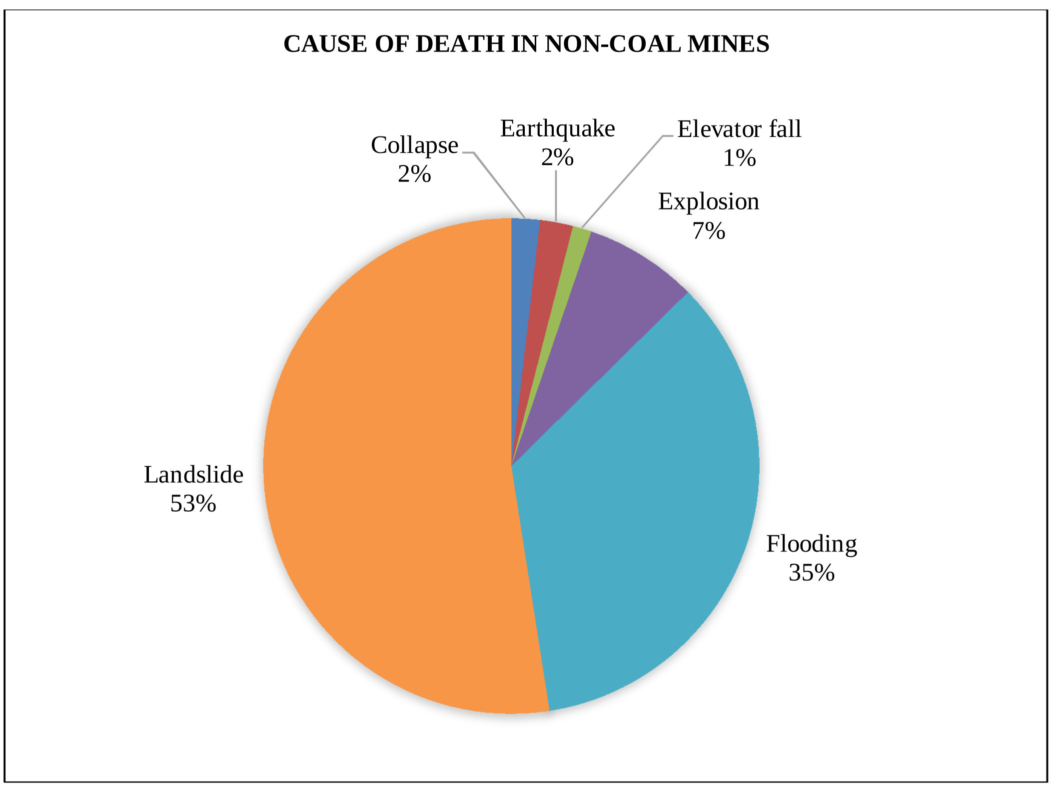


Figure 17 - Cause of death in selected AM disasters (non-coal) 1992-98

The same ILO's study reports a list of annual fatalities in artisanal mines in 23 selected developing countries: Bolivia, Chile, China, Cuba, Dominica, Ghana, Guinea, Guyana, India, Kenya, Malaysia, Mexico, Myanmar, Namibia, Nepal, Niger, Pakistan, Peru, South Africa, United Republic of Tanzania, Thailand, Zambia and Zimbabwe. The study also reports a list of the number of artisanal miners operating in those countries. Even if statistics reported statistics on AM can be sometimes far from reality (Seccatore et al., 2014), for consistency the two lists have been cross-examined because they represent an estimation of the AM situation in 1999. The result is ***Figure 18***, where are indicated the annual fatalities occurred per thousand of artisanal miners. This is an indicator used also by Chakravorty (2001), as discussed below.

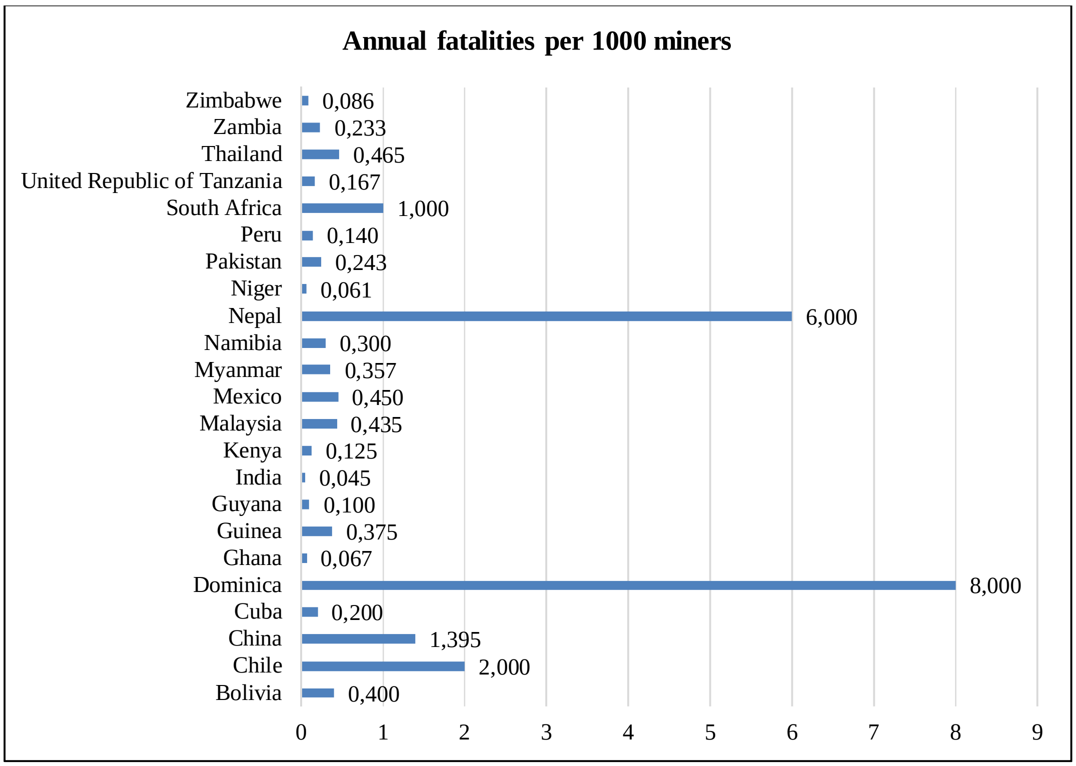


Figure 18 - Annual fatalities in AM in 23 selected developing countries in 1999

The case of the Merani Mine, Tanzania (1996-2002)

Hilson (2006) published an analysis of the causes of fatal accidents in the Merani Mine, in Tanzania. Data are analyzed in *Figure* ***19***. This is a first attempt to distinguish the causes of death in a single mine over a period of time, in order to understand the major hazards of the specific working site. Hilson comments on the poor condition of ventilation of the Merani mine, and indeed the main cause of death in this case is suffocation. Nonetheless, as discussed in the paragraph above, geotechnical accidents are the second issue (12%). Unsafe employ of explosives caused an overall 17% of the deaths.

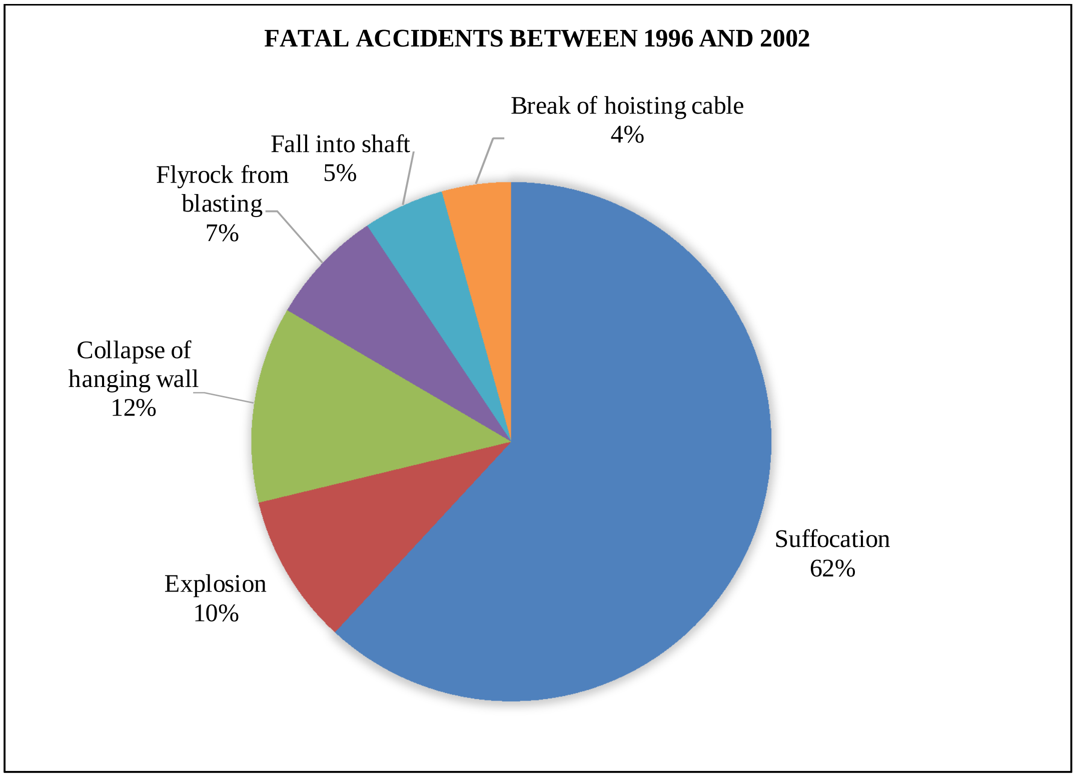
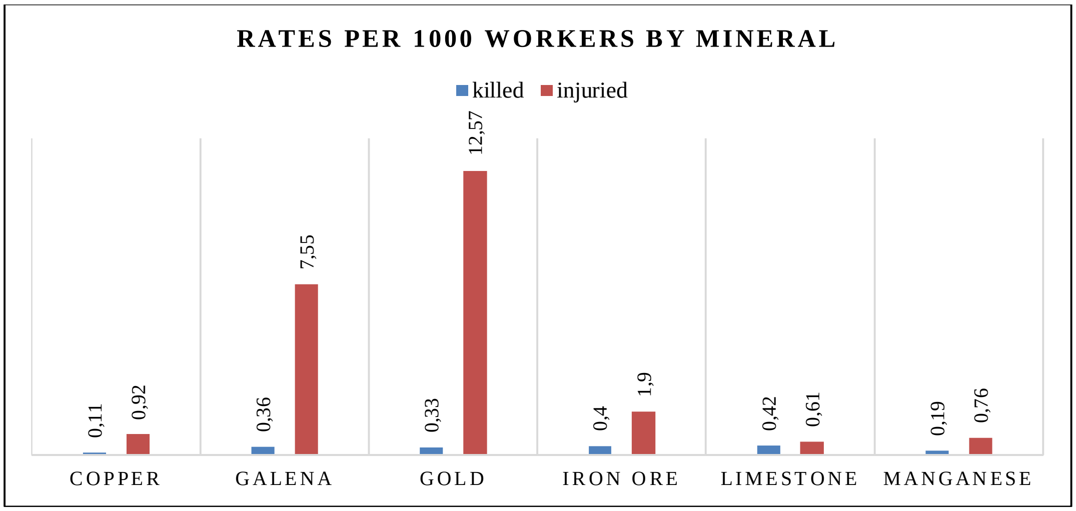


Figure 19 – Fatal Accidents at the Merani Mine

Artisanal mining accidents in India

Chakravorty (2001) wrote an extensive study on "Artisanal and Small-scale Mining in India". According to the author himself "I am not clear [*sic*] how to differentiate between Artisanal Mining and Small-Scale Mining". So, Chakravorty does not differentiate between Artisanal Mining (AM) and Small-Scale Mining (SSM) in his statistics. He states that "both AM and SSM are highly labor intensive and no mining equipment, except simple tools, are used in AM and in tiny SSMs. But in non-tiny

SSMs the workers quite often use some mining equipment and machinery". Chakravorty's study does not address causes or effects of accidents, but classifies accidents by the type of ore and the type of mining (underground, opencast or superficial). Chakravorty's data have been analyzed statistically here, and the results are reported in ***Figure 20.*** It is interesting to note that accidents rate is not appreciably different between underground and superficial operations. According to the author himself "accidents rate per 1000 persons employed is not appreciably different in the case of underground mines as compared to opencast mines". An attempt made by the author to relate accidents statistics resulted inconclusive, since no prevalent trend could be extrapolated.



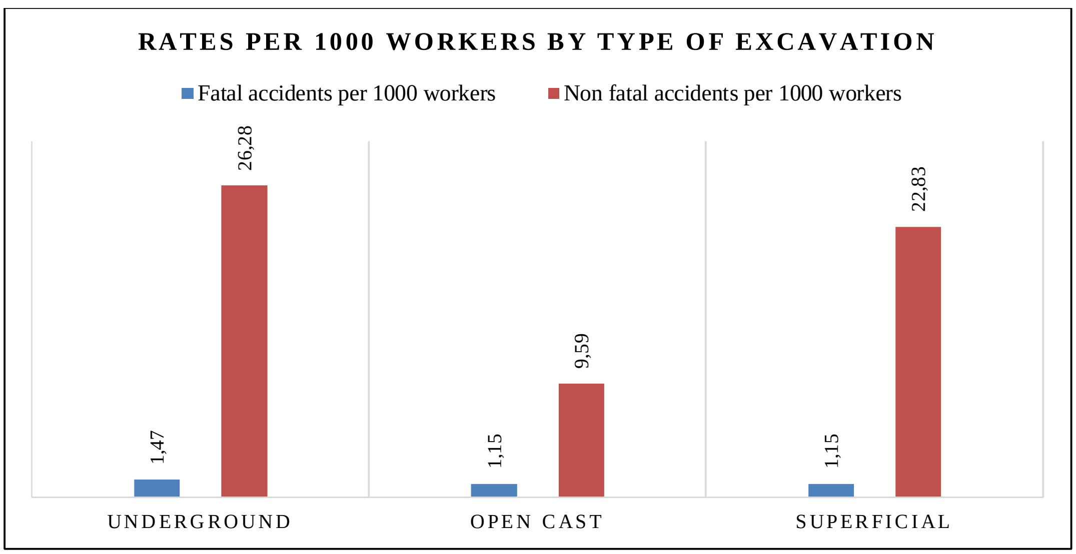


Figure 20 – Accidents rates per 1000 workers in AM and SSM in India

General Statistics

This section reports the highlights from studies on artisanal mining accidents and related injuries. Albeit not detailed enough to be characterized as proper JS&H analyses, these studies provide useful statistics that can be used as a basis for further studies.

Table 4 - Highlights of mining accidents and related injuries

Country	Statistics highlights	Method	Source
Ghana	Accidents involving small scale miners: 97.4 % Accidents in large scale mines: 2.6%. Accidents involving illegal miners: 95%. Causes of accidents: Collapse of the mine roof (46.7%) Falls (25%) Entrapment (22.2%) Type of hospitalized injuries: Crushing (19.4%) Clash-related injuries (19.4%) Fractures (9.7%) Spinal cord injuries (5.6%) Lacerations (4.2%) Known causes of hospitalized injuries: Collapse of the mine (12.5%) Blasts (9.8%). 2.9% of the hospitalized injuries were fatal.	Cross sectional study that examines the records of injuries affecting small scale miners: injuries presenting at the emergency department of a district hospital and reported injuries and accidents mainly among small scale gold miners in the media.	Clarke and, K-Amoah (2014)
China	6000 fatalities per year in SSM. 4500 - 5000 of these are in artisanal coal mines. 2046 Mine accidents between January and July. 3620 mine-related deaths in the same period. 67% of deaths induced by gas or coal dust explosion.	n/a	Hilson (2006)
Congo, D.R.	In Lupoto, province of Katanga, during the 12 months preceding the study: 392 accidents (72.2% of miners) Causes of accidents: Tools handling (51.5%) Handling heavy loads (32.9%). Factors such as age, seniority or apprenticeship did not generate significant differences. Types of injuries: Contusions (50.2%), Wounds (44.4%). Location of injuries: Upper limbs (50.5%) Lower limbs (29.3%). Physical sequelae were reported by 19% of the injured miners.	Based on a questionnaire administered in November 2009 to a sample of 180 miners	Elenge et al. (2013).

Recent accidents

In this paragraph are analyzed selected AM accidents for which is available sufficient information on the media, occurred since 2010 in developing countries. Data are resumed in Table 5: for each accident has been noted the excavation type, the main mineral extracted, the type of accident and the fatalities associated. It must be highlighted that media tends to report only accidents that caused deaths: neither accidents causing only injuries, nor the important “near misses” (accidents that did not cause any human damage but had the potential to do so) are reported. The first observation is that most of the accidents happened in gold mines, with the exception of the 2014 accident in Mexico (coal) and of the cases when the kind of mineral extracted is unreported in the news. This is explained by the contents of this Thesis: the shift in the price of gold since 2008 created a “gold rush” in gold mining, and AM, being the fastest response, increased in number of mines, operators and in production. It is a natural consequence that the number of accidents in AM of gold increased accordingly.

Table 5 – Selected AM accidents since 2010, from media

Country	**Year**	**Location**	**Excavation type**	**Mineral**	**Type of accident**	**Fatalities**	**Injured**
Sierra Leone	2010	Bo District	Open Pit	Gold	Trench collapse	200	
Congo	2012	Mambasa oriental district	Underground	Gold	Shaft collapse	60	
Chile	2012	Andacollo	Underground	-	Explosion	2	
Ghana	2013	Kyekyewere	Open pit	Gold	Landslide	16	4
Guinea	2013	Siguiri	Underground	Gold	Explosion	25	
Peru	2013	Camaná	Underground	Gold	Haulage system failure	2	
Colombia	2013	Andes	-	-	Handling of excessive load	1	
Colombia	2013	Buriticá	Mixed Underground/Open pit	Gold	Rock Collapse	10	
Ecuador	2013	Ponce Enriquez	Mixed Open Pit/Underground	Gold	Landslide	7	17
Colombia	2014	Buritica	Underground	Gold	Explosion	80	
Colombia	2014	Santander de Quilichao	Underground	Gold	Rockfall	16	
Mexico	2014	Coahuila state	Underground	Coal	Gas explosion	14	

Data are analyzed statistically in ***Figure 21***, ***Figure 22***, ***Figure 23***and ***Figure 24***. Accidents occur more in underground mines, but in terms of deaths underground and open pit mines have a similar proportion. This agrees with Chakravorty's data: accidents rate are not appreciably different between underground and superficial operations. Again, as discussed before, this can be attributed to the area or volume of influence: even if accidents underground are more frequent, a rock collapse in underground has a maximum impact size equal to the one of the tunnel, a landslide can have a maximum impact equal to the size of the slope of the entire excavation (see the accident in Sierra Leone in 2010).

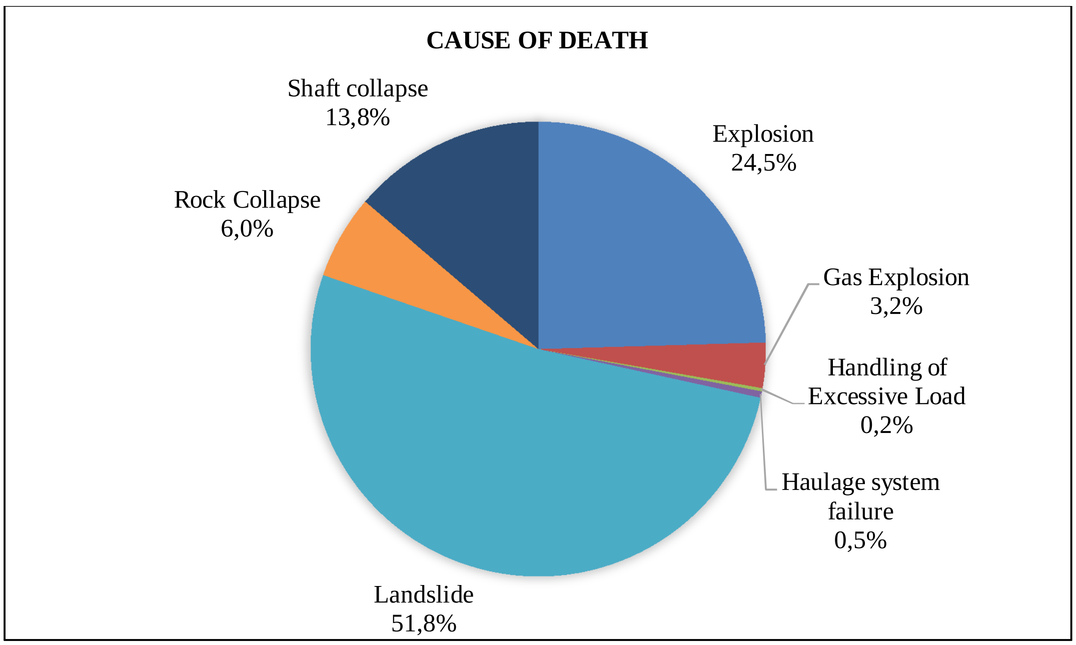


Figure 21 – Causes of death in selected AM accidents since 2010

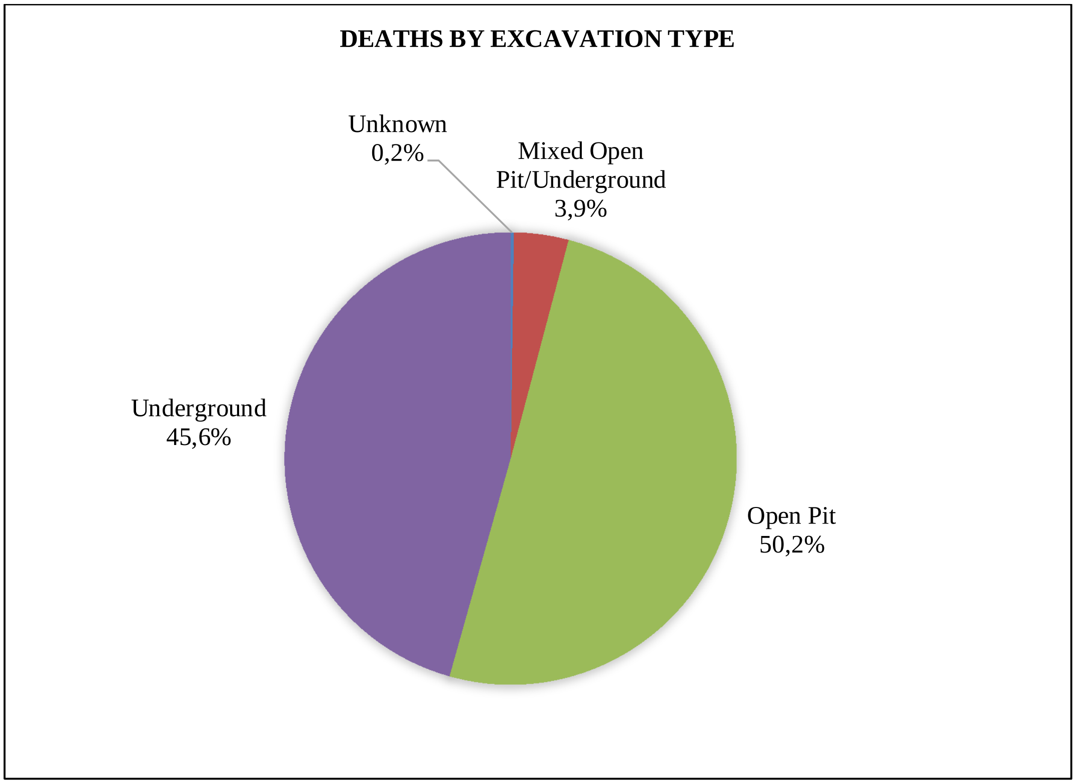


Figure 22 – Deaths by Excavation type adopted in the artisanal mines where selected accidents occurred since 2010

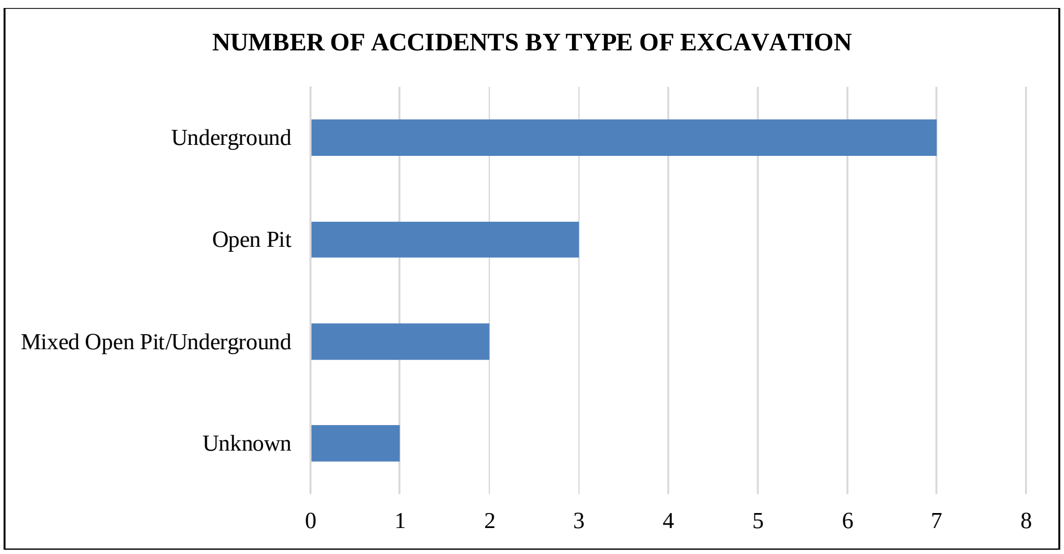


Figure 23 – Number of accidents by type of excavation

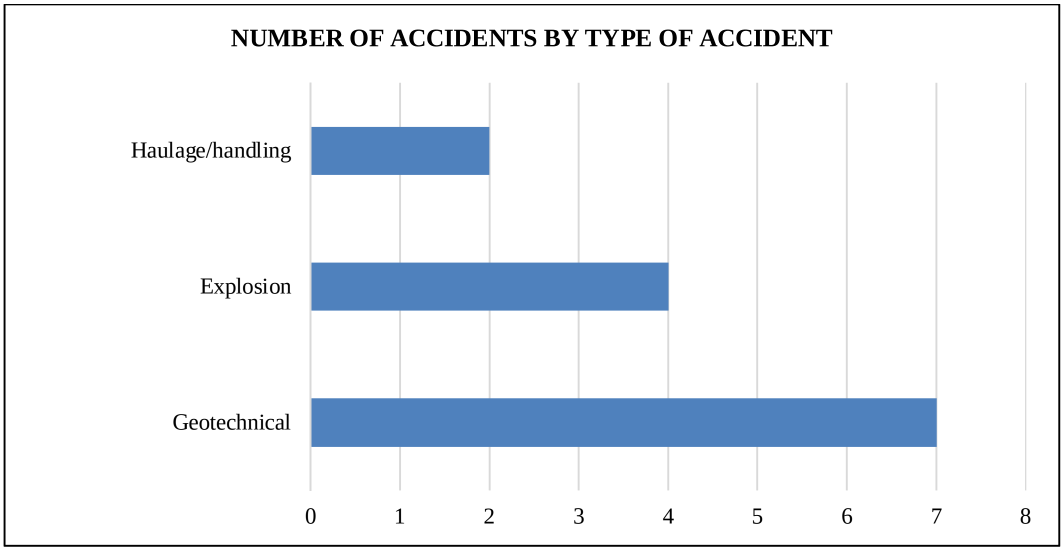


Figure 24 – Number of accidents by type

Discussion on AM accidents

Geotechnical and hydrogeological causes appear to be the most influential in terms of cause of accidents and of death consequences. According to the data analyzed, accidents tend to occur more in underground mines, but in terms of consequences (deaths) underground and open pit operations have a similar rate of occurrence. To explain this it is important to consider the area or volume of influence of the accidents: one single event with a large scale of impact, such a landslide at the scale of an entire slope, can produce more deaths than many accidents with punctual impact such as a roof collapse or an uncontrolled blast.

The main conclusion of this overview of AM accidents is that existing data is insufficient: field investigation must be encouraged and statistics have to be built. Statistics of occurrence are not enough for proper JS&H analysis. Inspections and databases must follow international standards such as the ones applied by the US Occupational Safety & Health Administration (OSHA). Only with such kind of reports of the accidents it would be possible a proper census and statistical analysis of such data would be adequate for Hazard Evaluation. To the end of basic characterization of AM, Chapter 4 of this thesis addresses Safety and Geotechnical stability issues, amongst other factors.

1.8 Final remarks

Resuming the literature sources consulted, some definitions can be given:

Small-Scale Mining (SSM) is a mining activity defined by low productivity (few hundreds of t/d ROM), low capital expenditure and revenues.
Artisanal Mining (AM) can be defined as a subset of SSM, falling in the same range of productivity and investment, but that possesses as well the characteristics of rudimentary mechanization, inefficient recovery, unsafe working conditions and labor exploitation.

As reviewed in the paragraphs above, AM is often so inefficient that there are treatment facilities that process waste simply abandoned by former artisanal activities. The potential for a technical sustainability (i.e. productive efficiency) exists, both in mining and in processing. It is also shown that the technologies that are more sustainable under an environmental point of view are also clearly more efficient under a technical and operational point of view. Advancing this potential efficiency and sustainability has a cost, even if low, and it needs a constant presence of highly specialized workers. Through the help of advanced engineering and high technical expertise a mining operation can become efficient, productive and sustainable independently from the scale of the operation. Consequently, a sustainable SSM is one that can get out of artisanal dimension (AM) and that can only be defined by the limit of its productivity.

There are obvious indicators of growth of SSM in the future. SSM meets both rapid customization to the needs of the market and the technological and financial flexibility to adapt to smaller deposits. These are all signs of a future development of small-scale mining of precious metals, especially gold, in the coming decades.

The economic sustainability of a SSM unit depends on a very effective optimization and innovation the operation. This is the key to be able to turn a small feature in a mineral reserve: in accordance with the approach set out by the Australia Code JORC (2004), the definition of a mineral reserve based on a resource (*Figure **25***) depends on the technical capacity of mining exploitation, together with other economic and governance considerations.

This conclusion is very important, because it clarifies that sustainability for SSM is strictly endogenous, and depends on its own ability to operate efficiently. When operational efficiency is achieved, sustainability comes as a consequence. When, through operational efficiency, an operation of SSM comes out of the artisanal condition, it becomes sustainable, and sustainability of surrounding livelihood and environment is strictly consequent. This is addressed in Chapter 5 of this Thesis.

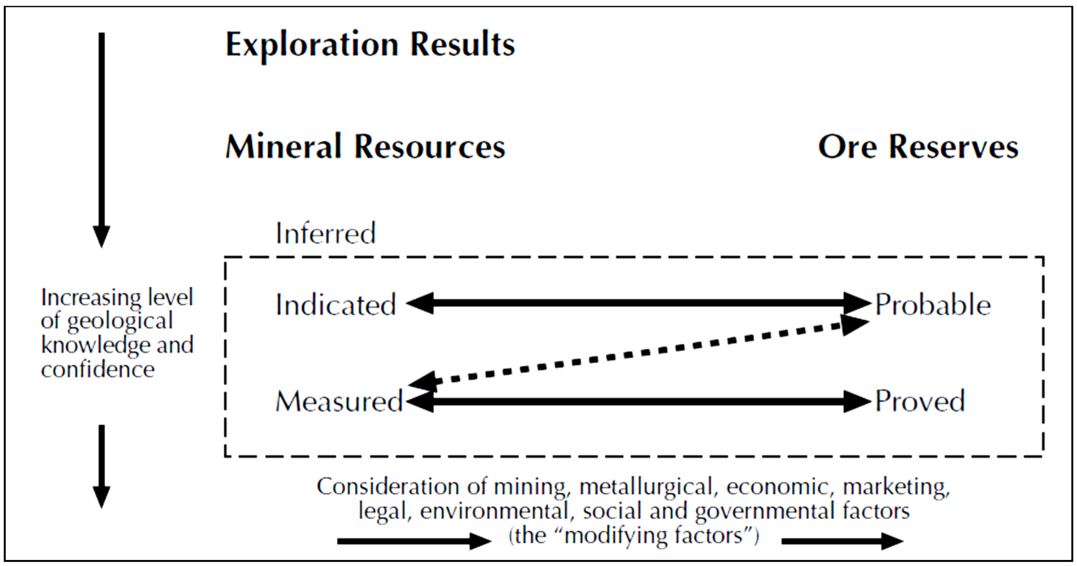


Figure 25 - General relationship between Exploration, Mineral Resources and Ore Reserves (JORC, 2004)

2 CHAPTER 2 - ESTIMATING THE ARTISANAL PRODUCTION OF GOLD IN THE WORLD

This chapter addresses the global impact of AM. In order to understand the potential for sustainability, it is necessary to define the size of the issue. Although it is known that the increase in gold price of the last years caused a shift in the production of artisanal mining (AM), this phenomenon has not been quantified yet. This chapter provides an estimation that gives an idea of the size of the potential for sustainability.

2.1 Estimation of the AM population in the world

Data show that a close relationship exists between the price of Au and the population of AM operators in the world. Quiroga (2002) estimated a population of 13 million AM operators at the time of publication. The same number is estimated by Hentschel et al. (2003) and Hinton et al. (2003). Eight years later Hruschka and Echevarria (2011) estimate an AM population of 25 million. The World Bank (2012) estimated a population of 20 million. In the same years AU price increased 417%: from an average 310 US$/oz (dollars per ounce) in 2002 to an average 1600 US$/oz in 2012, with a peak of 1700 US$/oz in 2011(GoldPrice, 2014). The data cited here are rough estimates, but a common trend is clear between Au price and AM population. Based on this observation, it is possible to calculate the shift in AM population during a given time, considering it directly proportional to the shift in Au price in the same period. This is shown in Equations 1 and 2.

References are available for general numbers of Artisanal Miners (AM) by country, regardless of mineral production. AM of Au is a percentage that can vary from almost 100% to none, depending on the country. The proportion of Au miners versus population influences the Au productivity per miner. This is taken into account when dealing with the adjustment factors described below.

The calculation of the AM population can be based on a relationship developed using the number of AM population per country using data obtained from reliable available sources, such as the *Report on Mining, Minerals and Sustainable Development* (MMSD 2002) and the *Communities and Small-scale Mining* online database (CASM 2012) online database. The complete list of sources is reported in the caption of ***Table 7***. The variation (percentage) in the price of Au can be calculated between the year of the reference (per each country) and the 2011 average Au price, updated to January 2012, as in equation1:

$$\Delta_{\text{Au price}}[\%] = \frac{\text{Price}_{2011}^{\text{Au}} - \text{Price}_{\text{year of reference}}^{\text{Au}}}{\text{Price}_{\text{year of reference}}^{\text{Au}}} \cdot 100 \qquad (1)$$

The same percentage shift, per country, can subsequently be applied to the AM population, obtained the updated current value, as in equation 2:

$$n_{2011}^{COUNTRY\ x} = n_{year\ of\ reference} \times \Delta_{\text{Au price}} \qquad (2)$$

Where *n* is the number of artisanal miners operating in the country *x*.

The analysis has been conducted in two different scenarios, being:

- Scenario 1: the “low-number scenario”: when two references with the same credibility were available per country, the lower number has been chosen to feed Scenario 1
- Scenario 2: the “high-number scenario” when two references with the same credibility were available per country, the higher number has been chosen to feed Scenario 2

2.2 Methodology

Estimation of gold produced by AM

Figure ***26*** of Chapter 1 (Veiga, 1997) is a precious tool. It shows the correlation between gold production and number of miners, and the data reported can be elaborated a little further if the intention is to use such a correlation for future evaluations.

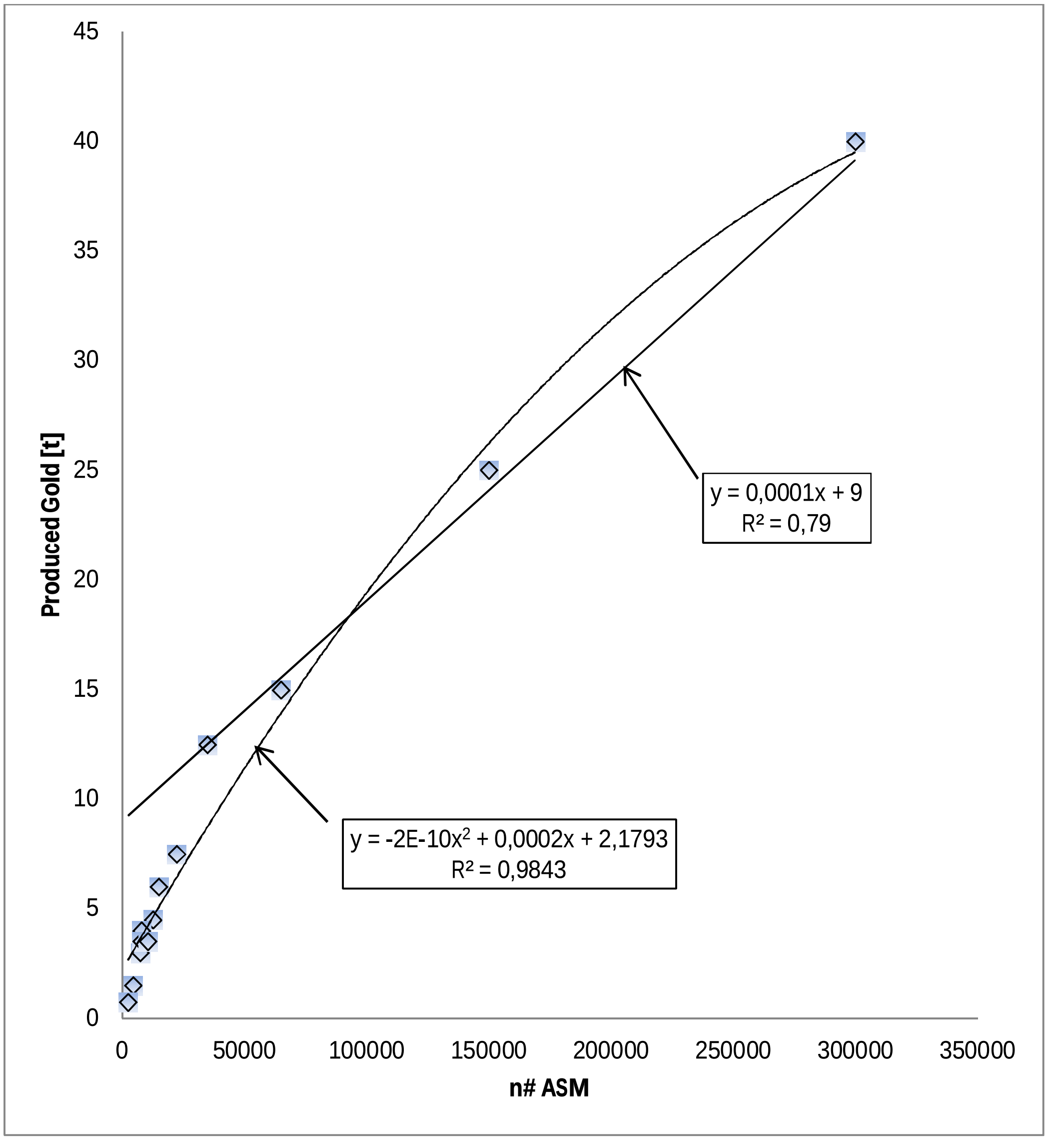


Figure 26 - Correlation between gold production and number of miners in Latin America (Data by Veiga, 1997, correlations by the author of this work)

As shown in the graph, data present two trends:

- A parabolic trend fitting lower values of AM population (n. AM < 300 000), as in equation 3:

$$P_u = -2 \cdot 10^{-10} n^2 + 0{,}002 \cdot n + 2.1793 \tag{3}$$

- A linear trend fitting higher values of AM population (n. AM > 300 000), as in equation 4:

$$P_u = 0{,}0001 \cdot n + 9 \tag{4}$$

Where P_u is the uncorrected production of Au of a given country [t] and n is the number of artisanal miners operating in that country. The two regression formulations can be applied to calculate the AM Au production by country. Nevertheless, using roughly these correlations on world AM populations would generate a heavy bias, since Veiga (1997) numbers came only from Latin American Countries. The correlation between the number of Au miners and their production depends on the type of ore (alluvial or hard rock), on the mining grade, the technology used, the level of mechanization, the level of instruction of the miners, the accessibility, and social and geopolitical conditions, amongst other factors. AM in Latin America is characterized by a higher technological level, and better access to ore, than in Asia and Africa. Thus, the production of Au per miner in other continents is expected to be lower. This estimation needs, hence, to be corrected.

The proposed correction was performed to estimate, for each continent, an adjustment factor, using ratios of technological impact factors in AM between Latin America and other continents. This is done as follows:

1. Equation 1 and 2 are used to calculate the population of AM in a given country
2. Either equations 3 or 4 (depending on the AM population of the given country) are applied to these results to calculate the uncorrected production of Au for the considered country.
3. An adjustment factor is calculated by continent, and applied by country according to its geographical position, according to Equation 6 and 7. Such factors take into account the different technological levels of the AM operations in the various continents. The method of determination of these factors is described in Paragraph 2.3.
4. The factors are then applied according to Equation 5. The final output is the estimated amount of Au produced by AM per country in 2011

.

$$P_{country\ i} = P_u \times C_{continent\ k} \tag{5}$$

Where $country\ i \in continent\ k$. $P_{country\ i}$ is the corrected production of Au in country x in 2011 [t], P_u is the uncorrected production of Au [t] and C is the adjustment factor for the continent k.

When available, an official reliable estimate of Au produced by AM has been inserted in Table 3 instead of the result of the calculations.

Adjustment factors

When looking at the AM productivity (grams of Au per AM capita) versus the AM population (*Figure* ***27***), a clear tendency appears between AM population and quantity of Au produced per capita: higher AM population corresponds to lower productivity per capita. This indicates, in general, that when fewer numbers of AM are operating, they possess a higher technological level for Au extraction. Nevertheless, even if the tendency is common when considering the world scenario, when looking at a sub-division by continent it appears clearly that each continent presents a different trend. South America has higher values, followed by lower values for Asia and much lower for Africa.

It must be considered that: a) data on AM productivity (grams extracted per miner) can be obtained only from sources that report both the population of AM and the amount of Au produced; and b) the number of sources containing reliable information about this is quite scarce. Therefore, it is necessary to find an average value per continent and apply this adjustment factor to every country for which information is not available.

The adjustment factor per each continent, hence, can be calculated comparing the average productivity per capita to the one of South America (on whose data Equations 3 and 4 were determined).

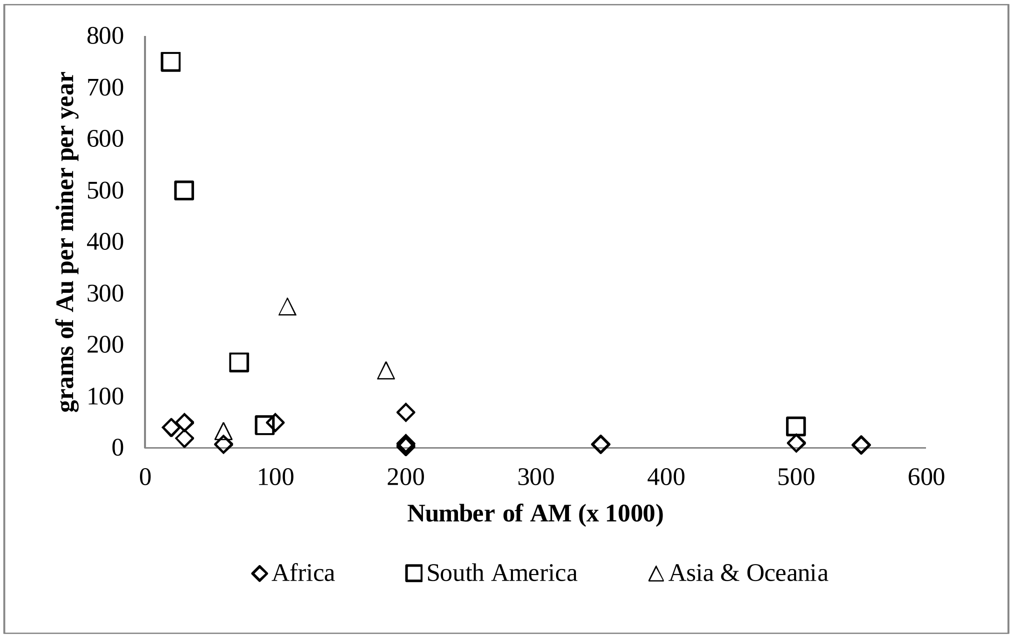


Figure 27 - Number of AM population vs. gold produced, by continent. The point for South America with high AM population and low productivity refers to Brazil, that has the largest AM population in the continent characterized by a lower technological level compared to other neighbor state. Overlapping diamonds at x~200.

The average production of Au per miner is calculated per continent, based on the available information in literature, according to Equation 6.

$$\bar{P}_{continent\ k} = \frac{1}{m}\sum_{i=1}^{m} P_{country\ i} \tag{6}$$

Where country i is in continent k. $\bar{P}$ is the average production of Au per miner per year in the continent k [g_{Au}/miner/year], $P_{country\ i}$ is the production of Au in the country i, and m is the number of countries analyzed for the given continent.

The adjustment factor of each continent is calculated according to Equation 7, based on the relationship between the average productivity and the highest one (the one from South America):

$$C_{CONTINENT\ k} = \frac{\bar{P}_{CONTINENT\ k}}{\bar{P}_{SOUTH\ AMERICA}} \tag{7}$$

The coefficients obtained are reported in *Table **6***.

Table 6 - Productivity per AM capita and productivity coefficients by continent

Average grams of gold per miner per year	
South America	300.4
Africa	20.6
Asia & Oceania	153.3
Coefficients	
South America	1
Africa	0.069
Asia & Oceania	0.511

The same coefficient for Central America was also applied to Asia, despite the fact that Central America's technological level is similar to South America, the number of AM actually extracting Au is a lower percentage than the rest of Latin American countries. This is an assumption based on the field experience of the authors, and is not based on literature references.
These coefficients are then applied in Equation 5, to obtain the amount of Au produced in 2011 per each country without a reliable source for Au production.

2.3 Results

The results for the two scenarios are reported in ***Table 7***. In this table "Estimate" means that the result came from the model above described, and not from a direct source. The coefficients calculated according Equation 7 have been applied in Equation 5 by country according to its geographical position. Those countries with no reliable information about AM were not included in this evaluation.

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Table 7 - Results of the estimation model, by nation. List of Sources: [1] DNPM (2010), [2] Infomine (2012), [3] Encyclopedia of the Nations (2012), [4] CASM (2012), [5] Mesfin (2012), [6] Hilson (2003), [7] Gold in South Africa (2004), [8] UNEP (2010), [9] Veiga (2012).

		Scenario 1		Scenario 2		
Continent	**Country**	**Expected AM population [x 1000]**	**Estimated gold production [t]**	**Expected AM population [x 1000]**	**Estimated gold production [t]**	**Source for gold production values**
Central America	Cuba	7	0.2	7	0.2	*Estimate*
	Mexico	56	0.9	56	0.9	*Estimate*
	Nicaragua	20	1.2	30	1.2	[9]
	Panama	63	1	63	1	*Estimate*
South America	Bolivia	130	24.8	130	24.8	*Estimate*
	Brazil	861	21	861	64.9	[1] + Estimate
	Chile	17	5.5	17	5.5	*Estimate*
	Colombia	268	41.4	418	50.8	*Estimate*
	Ecuador	128	24.5	128	24.5	*Estimate*
	French Guyana	7	3.6	7	3.6	*Estimate*
	Guyana	28	7.6	28	7.6	*Estimate*
	Peru	70	40	70	40	[2]
	Suriname	28	15	28	15	*Estimate*
	Venezuela	25	7	70	15.1	*Estimate*
Africa	Algeria	7	0.3	7	0.27	*Estimate*
	Angola	218	2.5	218	2.5	*Estimate*
	Benin	15	0.3	15	0.3	*Estimate*
	Botswana	15	0.3	15	0.3	*Estimate*
	Burkina	-	0.5	-	1	[3]
	Burundi	91	1.3	91	1.3	*Estimate*
	Cameroon	44	1.5	44	1.5	[4]
	Central African Rep.	291	3	291	3	*Estimate*
	Chad	146	1.9	146	1.9	[4]
	Congo Dem. Rep.	2910	5	2910	5	[4]
	Equat. Guinea	15	0.3	15	0.3	*Estimate*
	Ethiopia	728	5	728	5	[5]
	Gabon	36	0.6	36	0.6	*Estimate*
	Ghana	406	4.1	406	4.1	[6]
	Guinea	200	6	300	9	*Estimate*
	Guinea Bissau	7	0.3	7	0.3	*Estimate*
	Kenya	146	5	146	5	[4]
	Liberia	146	1.9	146	1.9	*Estimate*
	Lybia	7	0.3	7	0.3	*Estimate*
	Madagascar	437	3.5	437	3.5	*Estimate*
	Mali	361	1.7	361	1.7	[4]
	Morocco	73	1.1	73	1.1	*Estimate*
	Mozambique	291	3	291	3	*Estimate*
	Namibia	29	0.5	29	0.5	*Estimate*

	Niger	291	1	291	1	[4]
	Ruwanda	73	1.2	73	1.2	*Estimate*
	Senegal	15	0.3	15	0.3	*Estimate*
	Sierra Leone	437	3.5	437	3.5	*Estimate*
	Somalia	15	0.4	15	0.4	*Estimate*
	South Africa	37	17	37	17	[7]
	Sudan	291	3	291	3	*Estimate*
	Tanzania	994	2	994	3.5	[5]
	Togo	20	0.4	15	0.3	*Estimate*
	Uganda	218	2.5	218	2.5	*Estimate*
	Zambia	87	1.4	87	1.4	*Estimate*
	Zimbabwe	509	2.8	509	2.8	*Estimate*
Asia	Mongolia		5		5	[8]
	China	2746	48.2	2746	48.2	*Estimate*
	India	915	1.2	915	1.2	*Estimate*
	Indonesia	250	20.0	250	20.0	[3]
	Pakistan	515	8.9	515	8.9	*Estimate*
	Papua N.G.	108	2	108	5	[4]
	Philippines	366	28	366	28	[8]
	Vietnam	63	7.1	63	7.1	*Estimate*
TOTAL		16,027	379.4	16,327	448.7	

2.4 Influence with mercury consumption

Hg consumption data analyzed in this section was taken from the online database MercuryWatch (2014). The present work refers to the "Hg consumed" ($Hg_{consumed}$ or Hg_{lost}) by artisanal miners. This is the mercury consumed during processing and lost to the environment (air, water, and soil). This is different from the "Hg used" (Hg_{used}) as it is often employed in large excess and then recovered by means of retorts, squeezing through clothes or other ways. Hg “consumed” depends on the processing technique adopted by artisanal miners as well as on the type of ore being processed, and has a strong relationship with the technological level of the AM process. Here, the results of the high-number scenario (Scenario 2) are compared to the values of Hg consumption from the online database to generate a $Hg_{consumed}$:$Au_{produced}$ ratio (often referred to as Hg_{lost}:$Au_{produced}$, it is written as “consumed” in this discussion to highlight its role of technological indicator more than of environmental hazard). It is used for the high-number scenario because it is the one where Au production is considered higher, and therefore gives a more conservative Hg:Au ratio.

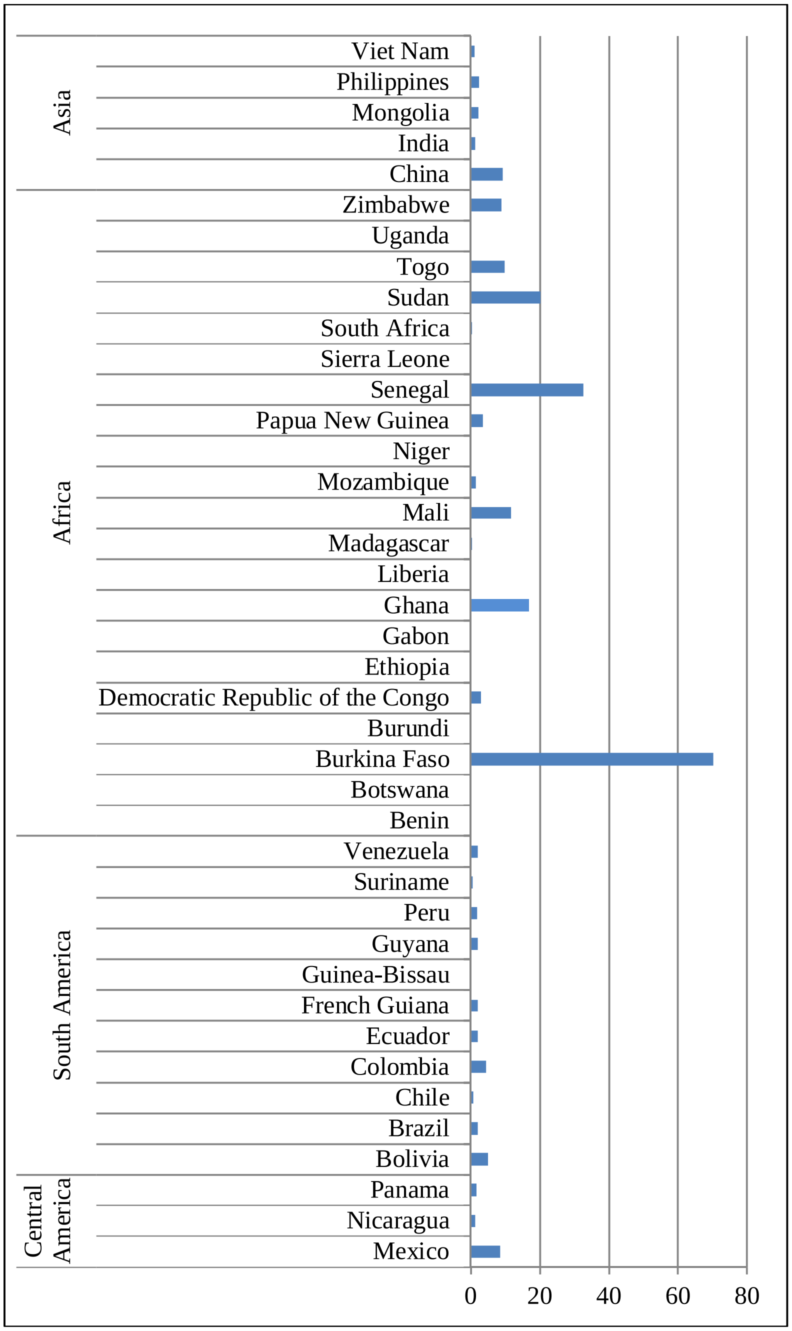


Figure 28 - Ratio of Mercury Consumed over Gold Produced, by country per continent

The highest Hg:Au ratios are calculated for Africa, and the lowest in South America. *Table **8*** shows the comparison between the mean of the ratio $Hg_{consumed}$:$Au_{produced}$ and the adjustment factors. As said, such factors reflect the technological level (therefore the efficiency) of the AM process. These results indicate a higher level of ore processing efficiency in South America> Asia =Central America> Africa.

Table 8 – Comparison between the Adjustment Factors used in the model and Ratio of Mercury Used over Gold Produced by continent

Continent	Adjustment factor	Ratio $Hg_{consumed}:Au_{produced}$
South America	1	2.0
Africa	0.069	8.5
Asia & Oceania	0.511	3.3
Central America	0.511	3.8

2.5 Resume and discussion of the results

The results are reported in ***Table 7*** and resumed, by continent, in ***Table 9***. The gold produced by AM is approximately 15% of official gold production in the world, in 2011, 2,660 t (U.S. Geological Survey, 2013).

Table 9 – Estimated values of gold produced by AM by continent

Continent	Estimated AM gold production [t]	
	Scenario 1	**Scenario 2**
Central America	3.30	3.30
South America	190.40	251.80
Africa	85.26	90.16
Asia	100.40	103.40
TOTAL	379.36	448.66

It is important to reiterate that formal and reliable sources on occupation and production of artisanal mining of Au in the world are very scarce. Therefore, the aim of the present model is to provide an estimate. Field research, census, and control over the AM phenomenon would reduce the uncertainty.
The global characteristic of artisanal Au production that may be governed either by the level of the technology available, or type of ore mined and treated is evident based on percent production by continent (Table 5).
This model, for its very nature, is not precise, but a first approximation. The results here reported give a reliable order of magnitude of the production of artisanal mining in the world, of the people involved in such production, and the technological levels employed in the different parties of the world. The comparison with Hg consumption reported by independent sources confirms the assumptions made to create this model.

This model must be still validated by comparing the results with consistent and reliable data coming from on-field census, and eventually adjusted accordingly.

2.6 Final remarks

Based on a first approximation, between 380 and 450 t of Au are produced annually by ~16 million artisanal miners in the world. A global trend in Au recovery was observed. As a consequence, adjustment factors were introduced to account for the different technological levels of the AM process across continents: higher for Latin America, lower for Asia and Central America, and lowest for Africa. The comparison with Hg consumption reported by independent sources confirms such assumption.

Correlation of Au production with Hg consumption show a correspondence between the adjustment factors adopted and the Hg:Au ratio: the AM process is more efficient in South America, less efficient in Asia and Central America, and least efficient in Africa. The relationship with Hg release and contamination and technology is direct.

As said above, other factors such as the geological differences between the countries and continents can be influential, but at this stage of the research there is no way of quantifying such influence. It must be assumed that the technological level, represented by the key indicator Hg:Au ratio, is the most influential factor. A dedicated study should address the influence of mineralogy in artisanal Au recovery, amongst other factors.

The present model is a reliable tool for a first approximation, but it must be still validated comparing the results with consistent and reliable data, and eventually adjusted accordingly. Field research and census must be strongly encouraged with this purpose.

2.7 Acknowledgments

The original stage of the study object of this chapter has been commissioned to me by the World Gold Council, London, UK, by the person of Ditlev Schwanenflugel, due to my research activity in the field of SSM. I am very grateful to Mr. Schwanenflugel for the idea and the financial support. I also thank very much the helpful suggestions offered by Prof. Kevin Telmer, University of Victoria, about the use references on mercury. Chiara Origliasso helped me a lot in the detailed bibliographical research of references.

3 CHAPTER 3 – ADDRESSING THE SUSTAINABILITY OF SMALL-SCALE MINING

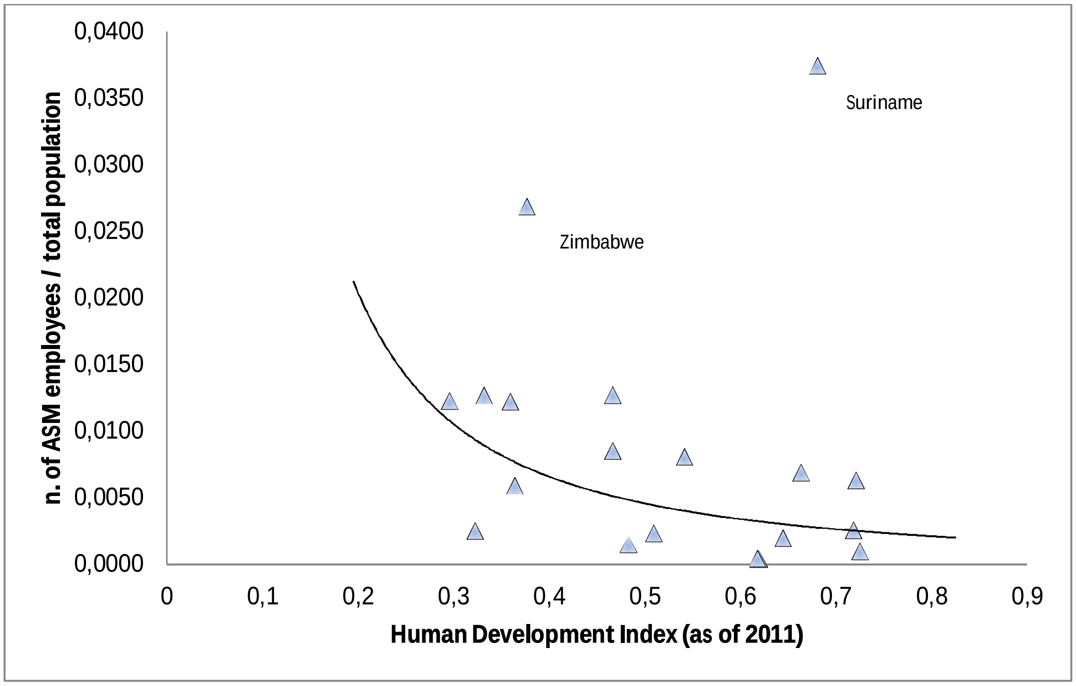
This chapter discusses whether a Small Mining unit can be assessed as sustainable, and which is the path needed by SSM towards sustainability.

*Figure **4*** of the first chapter shows data by Hoadley & Limpitlaw (2004) indicating that the proportion of artisanal miners over the total population of a country is inversely proportional to the Human Development Index (HDI) of the same country. Nevertheless, some deeper investigation can be tried in order to effectively understand what lies behind the relationship between AM (the not-sustainable subset of SSM) and the HDI. The proportion of artisanal miners over the total population is an interesting indicator, but it only gives information regarding the presence of AM in a country, not regarding its operational aspects. The gold recovered by this population is be a more interesting indicator to analyze the operational aspect of AM. With some data available this can be easily achieved.

Data used here are the same used in the previous chapter, but limited to countries with a reliable reference (results from the model are not interpreted here). Simply dividing the yearly production of gold artisanally produced by the number of AM workers, the production of gold achieved per capita of AM worker can be found. This production per capita is an index of the technological level of AM in that country: the higher the production per capita, the more efficient is the extraction. The result is compared to the Human Development Index (HDI) of each country. The values of the HDI were used referring to the most recent year of the Human Development Report previous to the references of Chapter 2 (UNPD 2011). The result of this comparison is shown in *Figure **29***, where a clear tendency is visible. The trend of the regression line shows that efficient mining and treatment (higher number of grams per capita) corresponds to a more sustainable livelihood (higher HDI). This does not mean that more efficient artisanal mining causes a higher HDI (correlation does not imply causation). This just means that more efficient AM happens in countries with higher HDI. This result can be seen as a significant indicator of the validity of our thesis: higher efficiency in mining corresponds to higher sustainability.

Table 10 – AM, productivity and HDI in selected countries for which literature sources are available (Sources: CASM Database 2012 and MMSD 2002 for information on AM, UNPD 2011 for the HDI, Worldometers Database 2012 for the information on total population of each nation)

Country	n. AM (x 1000)	grams of gold per miner	total population	n. AM / tot. pop.	H.D.I.
Bolivia	72	166,7	10426	0,0069	0,663
Brazil	500	42,0	192376	0,0026	0,718
Burkina Faso	200	2,6	15731	0,0127	0,331
Cameroon	30	18,9	19406	0,0015	0,482
Ecuador	92	43,5	14483	0,0064	0,72
Ethiopia	500	10,0	84321	0,0059	0,363
Ghana	200	70,0	24659	0,0081	0,541
Indonesia	109	275,2	237641	0,0005	0,617
Kenya	100	50,0	42749	0,0023	0,509
Mali	200	8,5	16319	0,0123	0,359
Mozambique	60	8,0	23701	0,0025	0,322
Niger	200	5,0	16275	0,0123	0,295
Papua N.G.	60	33,3	7014	0,0086	0,466
Peru	30	500,0	30136	0,0010	0,725
Philippines	185	151,4	92338	0,0020	0,644
South Africa	20	40,0	50587	0,0004	0,619
Suriname	20	750,0	534	0,0375	0,68
Tanzania	550	6,4	43188	0,0127	0,466
Zimbabwe	350	8,0	13014	0,0269	0,376



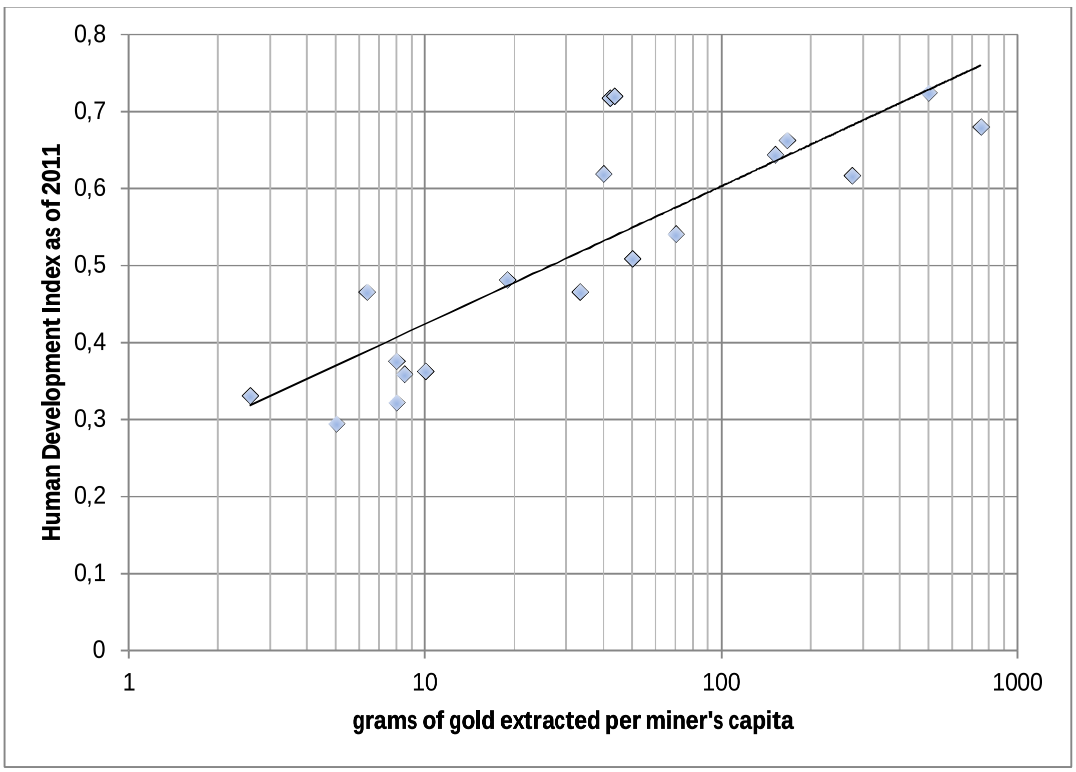


Figure 29 – Comparison of correlations between AM in a country and the HDI of the given country: HDI Vs. proportion of artisanal miners over the total population (above); grams of gold extracted per miner's capita Vs. HDI (below)

What is discussed above is a pivotal point in the discussion on the sustainability of sustainability in SSM: higher technical efficiency corresponds to (but does not necessarily cause) a higher sustainability of livelihood. Any effort in the sustainability of SSM, and in the passage from AM to a sustainable form of SSM, must pass through the technical and economical sustainability of its operation. When a SSM operation comes out of the AM condition, it is made sustainable and the sustainability of the surrounding livelihood and environment is strictly consequent.

3.1 An assessment of the sustainability of SSM based on the analysis of two real cases

This paragraph contains a comparative study of two artisanal underground mines visited and analyzed during field work between Ecuador and Peru. The two cases are very different one from the other under the point of view of geological bodies, type of mining methods, scale and characteristics of technical and production parameters. Nonetheless, one of the two mines appears as a totally artisanal and rudimentary operation, while the other, although still at a small and artisanal level, possesses characteristics of responsible mining and appears much more viable than the other in environmental, operational and economical terms. The fact is that not only technical aspects enter the definition of sustainability of an AM site. Aspects of governance, management and financial investment are strictly related to the viability of such operations, and are strictly linked to the technical aspects in a way that cannot be separated. In the next paragraphs will be analyzed the conditions that define these operations viable, and some of their indicators will be individuated.

Ecuadorian Mine

This mine is located in the province of El Oro, in Southern Ecuador, an area historically dedicated to gold extraction since the pre-Columbian age (since the name: “El Oro” means “The Gold”). The whole area has been exploited on large-scale at an industrial level by a USA-based company (South America Development Company – SADCO) from 1896 till the 1950s. The property of the mineral rights, of the network of tunnels and all of the external structures then passed to a publicly owned Ecuadorian company (CIMA), and finally closed in the 1980s (Cortazár & Lavanda, 2008). The actual owner, as well as many other artisanal miners in the area, is mining a small portion of that area from the tunnels left by the SADCO and CIMA operations. Besides operating at an artisanal level, both the owner of this mine and the majority of the others in the area are legally exploiting an area regularly registered as a mining concession in their own names.

Local geology is mainly Andesite as the embedding rock. Gold occurrences appear in geods of porous quartz along quartz veins 0,7 to 1 m wide, in association with Iron (in the forms of oxide and of sulphite as pyrite), Copper (chalcopiryite) and Zinc. The mining activity is carried on by drilling & blasting. The tunnels have a rough rectangular section of 2 m wide x 2,5 m high. Drilling is performed with manual jack-leg pneumatic drills. The explosives used are emulsion as a booster and ANFO in cartridges as column charge. The charges are primed by fire cap and safety fuse, the last ignited manually with a lantern, obtaining timing only by the length of the fuses and the sequence of ignition. Technical details of this operation are reported in ***Table 11***. Electricity, water and compressed air are supplied from outside the mine till the excavation face by lines and pipes. Transport of material is achieved by wagons pulled by a small electric locomotive. Production is performed over 2 daily shifts. The third shift is dedicated to natural ventilation, since no system of fans is installed. Detailed information about the production of the mine is reported in ***Table 12***. No exploratory drilling is performed by the owner of the mine. Geological knowledge is based on outcrops, information from previous explorations made by third parties, and notice of minerals occurrences heard through the “grapevine” network of the local miner’s community. Tunnels are driven as the main way of geological exploration, in the hope of crossing a mineralized vein to begin exploitation along it. The financing of the operations comes from the revenues of a processing plant that the mine owner possesses as well. This plant processes gold and other minerals coming from many others mines, and is economically active enough to finance the excavations and support the eventual losses in the mine’s operations.

Peruvian Mine

The mine is located in the department of Piura, Province of Ajabaca, district of Suyo , in Northern Peru. The area has been only recently exploited by artisanal miners, and quartz veins have been excavated underground just in the last years. All the artisanal mining operations in the area are illegal (according to the D.L. 1100, 1101 and 1102/2012 of the Peruvian Regulatory system), and strong political tensions have grown between the

Peruvian government and the local artisanal miners due to this. The mine exploits auriferous quartz veins embedded mainly into a clay-shale formation, whose bedding is parallel to the one of the veins. The auriferous veins consist of porous and heavily altered quartz, with iron in the form of oxide (near the surface) or sulfide as pyrite (deep underneath). The presence of iron is used as a visual reference to choose the direction of excavation.

For the development of the mine, no planning method is recognizable at all. The shape, bedding and dimension of the orebody is totally unknown to the miners, since neither exploratory drilling nor extended geological survey has ever been performed. The decision-making process is based on the positioning and qualitative evaluation of the bedding of the veins' outcrops. Auriferous grades are evaluated through commissioned laboratory tests, and the veins are followed according to the grades. When a vein is encountered in an outcrop, a tunnel, with very irregular section, is usually excavated to follow it (see ***Figure 31***). Later, main shafts and other lateral tunnels are excavated from the surface both to provide ventilation and to cross the vein perpendicularly at lower levels. When the mineral grade is high and the width and lateral continuity of the vein are suitable for large exploitation, sub-vertical stopes are excavated along the bedding of the vein, in an artisanal form of "stope and pillar" method.

The excavation is carried on by drilling and blasting. Drilling is performed with a portable electric drill using twist drill bits. There is no employ of the opening cut technique. Holes are charged with Dynamite cartridges primed with a fuse cap and ignited by safety fuse.

The work shifts are organized 3 per day, each of 8 hours. Technical details of the excavation are reported in ***Table 11***. The transport of the mineral is achieved through plastic buckets and a wagon moving along a slide inside the main shaft. Production details are reported in ***Table 12***. Due to the mazy shape of the network of tunnels and shafts, ventilation is very bad and the quality of the air extremely poor in many points.

The product of the mine is the ROM material: the owner sells it to third-party treatment plants. The revenues of this selling are the only source of financing of the entire operation.

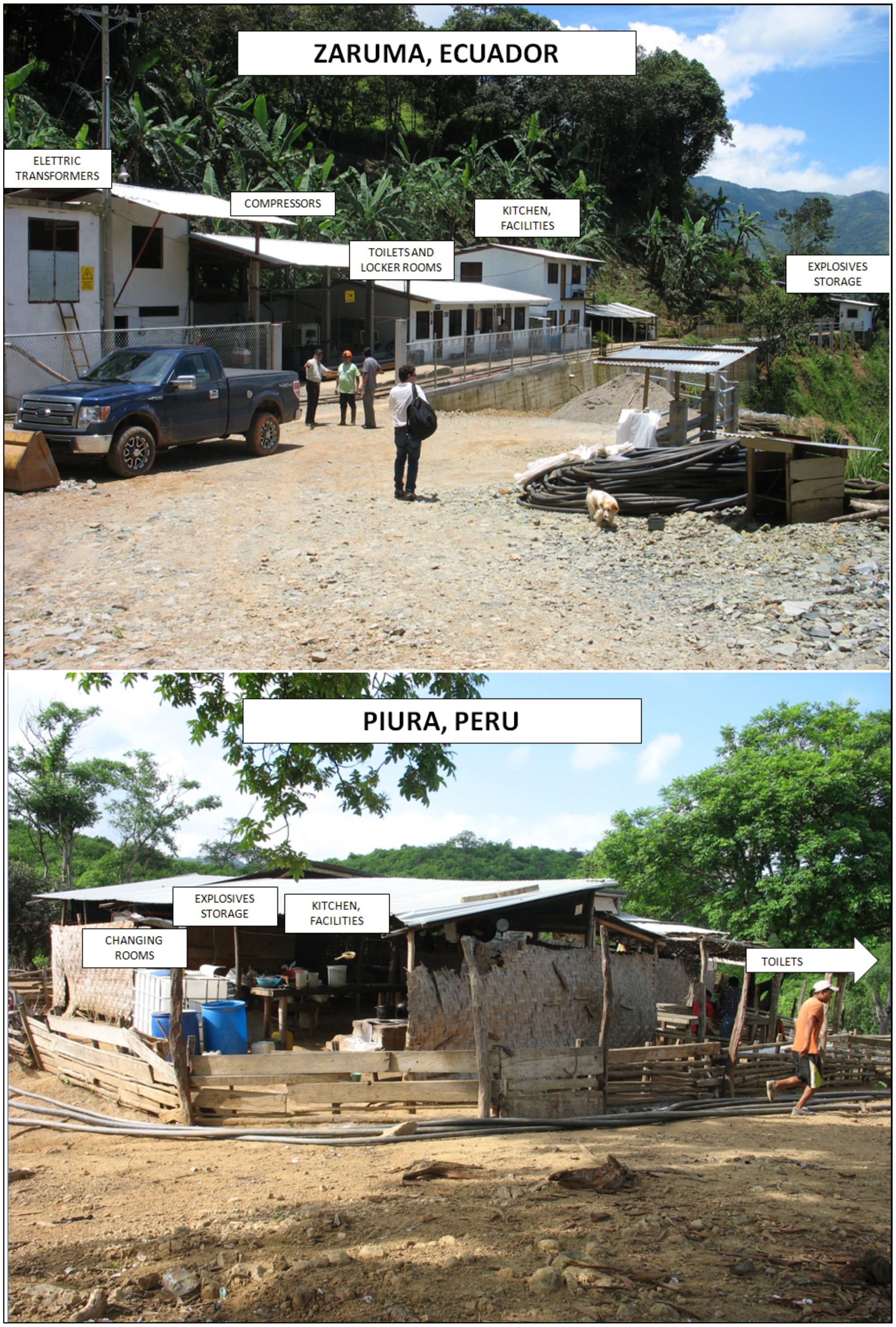


Figure 30 The main facilities of the two mines.

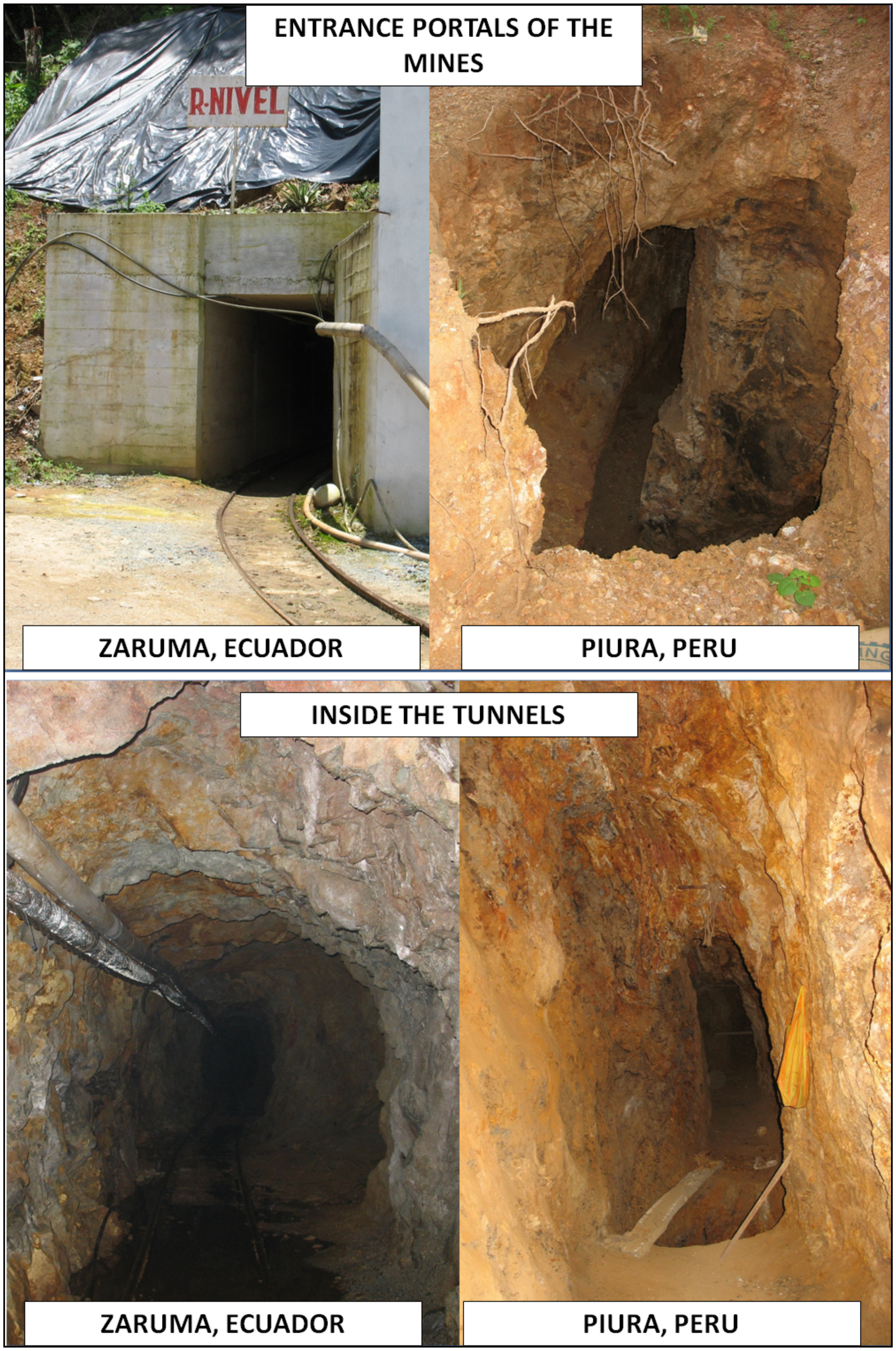


Figure 31 - Accesses and tunnels of the two mines

Table 11 - Comparison of technical parameters of the drill & blast excavation in the two mines

Symbol	Parameter	Unit	Values	
			Ecuador	Peru
S_h	Design Section height	[m]	2.50	-
S_w	Design Section width	[m]	2.10	-
Ad	Design Section	[m²]	5.25	1.53
Aa	Actual Blasted Section	[m²]	4.20	1.00
μa	Section Efficiency	-	0.80	0.65
L_d	Design Pull	[m]	1.60	0.90
L_a	Actual Pull	[m]	1.28	0.30
μp	Pull Efficiency	-	0.80	0.33
V	Blasted Volume	[m³]	5.38	0.3
ρrock	Rock density	[kg/m3]	2.65	2.5
T	Tonnage of one blast	[t]	14.25	0.75
Φ	Hole diameter	["]	$1^1/_4$	1
Q	Charge per hole	[kg]	1.56	0.13
L_Q	Charge lenght	[m]	1.00	0.18
N	N. of holes	-	28	10
Q_{TOT}	Charge per round	[kg]	43.60	1.80
P.F.d	Design Powder Factor	[kg/m³]	5.19	1.18
P.F.a	Actual Powder Factor	[kg/m³]	8.10	1.80

Table 12 - Comparison of production parameters in the two mines

Parameter	Unit	Values	
		Ecuador	Peru
Producion (ROM tonnage) per blast	[t]	14.25	0.75
Blasts per shift	[t]	1	2
Production per shift	[t]	14.25	1.50
Shifts per day	-	2	3
Daily production	[t]	28.49	4.50
Working days per week	-	5	7
Miners per shift	-	5	8
Average grade	[g/t]	6	18
Gold extracted daily	[g]	170.96	80.33
Daily Tonnage per miner's capita	[t]	2.85	0.19
Daily Au extracted per miner's capita	[g]	17.10	3.35

Indicators of Sustainability

As it appears from what described and showed in the paragraphs above, the situation of the two mines is quite different. Nonetheless, none of the reported parameters indicates precisely whether one of the mines is more or sustainable than the other, nor whether it is sustainable at all by itself. To understand this, one can look at the indicators already used in literature to characterize small-scale mining, as the ones reviewed in Chapter 1. This paragraph contains lists of indicators for AM viability extracted from various literature sources: over each lists check-tests have been performed in order to compare the realities of the two mines object of this study, and to obtain a clearer view of the inherent differences between them.

Table 13 - Common characteristics of artisanal and small-scale mining activities (MMSD, 2002)

Indicator	Ecuadorian Mine	Peruvian Mine
Exploit of marginal deposits.		
Lack of capital.		X
Labor-intensive		
Low rates of recovery.		
Poor access to markets and support services.		X
Low standards of safety and health.		X
Significant impact on the environment		

Table 14 - Characterizing aspects of Artisanal Mining (Hilson, 2002)

Indicator	Ecuadorian Mine	Peruvian Mine
Mining in alluvial deposits near the surface		
Intense labor activity		
Remote and isolated location		X
Rudimentary techniques and low technological knowledge		X
Low degree of mechanization	X	X
Low levels of environmental, health and safety awareness		X

Table 15 - Criteria for a mining activity to be defined sustainable: (Almeida & Torrens, 2002)

Indicator	Ecuadorian Mine	Peruvian Mine
Improvement of mining	X	
Improving safety conditions in the mine	X	
Mitigation of environmental impact	X	
Using the right equipment for the conditions of each site		
Rational and comprehensive use of mineral resources and mineral community benefits		
Reduction of geo-environmental and geodynamics threats and hazards		

Table 16 - Different factors influencing the willingness of the small-scale miners to operate legally (Hentschel et al., 2002)

	Indicators	Ecuadorian Mine	Peruvian Mine
Legal and administrative factors	Existence of coherent legal bases (mining code, rules, laws etc. in force)	X	X
	Existence of human, financial and material resources to enforce the laws (incl. decentralized structures)	X	
	Existence of the political will to execute the laws (incl. control and sanctions on infractions)	X	X
	Transparent and efficient mining administration (management of mining titles etc.)	X	
Economic factors	Existence of direct (access to finance, direct subventions etc.) and indirect (taxation, technical assistance etc.) incentives to produce legally	X	
	Possibility to use the legality of production as a marketing argument (fair trade etc.)	X	
	Existence of "win-win-options" (economic vs. environmental, social, cultural, legal etc.) for the normalization of the production	X	
	Economic opportunities with the marketing on the formal markets and local transformation	X	
Factors related to the enterprise	Investment security	X	
	Awareness of the importance of legal production in front of the risks related to illegality (possibility of sanctions, blackmailing, etc.)	X	X
	Professionalism of the entrepreneur and his staff	X	
	Financial capability and willingness to invest in the mining activity	X	
	Qualified personnel	X	
	Preparedness to realize changes in the legal, technical and organizational outline of the enterprise	X	
	Access to mining technologies and specialized mining services	X	
	Favorable investment climate	X	
Moral factors	Pression and interest of the public, the communities and other actors in favor of legal operations	X	X
	Consciousness of the clients about the origin and manner of production of mineral commodities	X	
	The production of large scale mining operation serves as positive example	X	X
	Public opinion against informality, corruption etc.	X	X

3.3 Discussion

The analysis of these indicators gives a more effective answer to the question "What is the real difference between the two mines?". The Peruvian mine possesses most of the characteristics attributed to artisanal mining, while the Ecuadorian mine presents just a few. On the other side, the Ecuadorian mine possesses most of the "factors influencing the willingness of the small-scale miners to operate legally" indicated by Hentschel et al., that can be read as "factors influencing the willingness of an external investor to invest in the mine". As said at the beginning of this chapter, the path towards sustainability for small-scale mining goes through efficiency. To achieve efficiency, investment is needed, for no innovation is free of costs. An external capital injection to invest in innovation is obviously discouraged by the artisanal aspect of the operation, while is encouraged by indicators of a rational and legal operation. The Ecuadorian mine is operating in a favorable condition: as shown by the indicators, it possesses the potential for sustainability. The Peruvian mine is far away from this point: indicators show that it is an artisanal operation that must be rationalized and given the conditions to operate legally before any investment for innovation can be done.

3.4 Answering the question: CAN SSM BE SUSTAINABLE?

Limiting the definition of sustainability in the mining business, it has been demonstrated that small-scale mining has the potential to be a sustainable form of mining. It has been proven: higher technical efficiency corresponds to a higher sustainability of livelihood. The path for sustainability goes through efficiency.

Efficiency has costs: the cost to innovate the operation towards effective methods using adequate technology and optimized equipment. This cost must be covered by an investment, and when the cost is high (for a high leap in innovation), it is most likely to come from outside of the small-scale mining enterprise: external investment.

Existing indicators from literature function very well to show how close or far a small-scale is from the artisanal dimension, that is the kind of operation that discourage an external investment. Nevertheless, more dedicated indicators should be found. To such a purpose is dedicated Chapter 4 of this Thesis.

PART 2 – HOW CAN SSM BE EVALUATED AS SUSTAINABLE?

4 CHAPTER 4 – IDENTIFYING BASIC INDICATORS FOR THE CHARACTERIZATION OF UNDERGROUND ARTISANAL MINES

This chapter attends the demand of Chapter 3 and discusses how can be evaluated the potential for AM to be turned into a sustainable SSM.

The discussion of this thesis addresses mainly underground SSM operations. This might seem strange and a-typical, but it has an explanation.

As thoroughly explained in the above chapters, artisanal small-scale mining (AM) is typically dedicated to the exploitation of marginal deposits of very valuable materials (such as gold, diamonds and other gemstones), with the profitability of such activities, despite their low efficiency and productivity, resulting from the high market prices of these commodities. It is true that until recently, AM was performed almost exclusively in easily accessible areas such as alluvial or low-consolidated deposits located near to the natural surface. Indeed, Hilson (2002) defined AM as “mining in alluvial deposits near the surface”. Underground mining of deep deposits was essentially out of the reach of artisanal operations until a few years ago. Veiga (1997) argued that:

> When these [*artisanal*] miners begin to extract gold from quartz veins, this is the beginning of the end of their activities, i.e. they do not have technology, geological information or capital to invest in underground mining and the result is usually bankruptcy

However, although conceiving AM as an exclusively surface mining activity was previously valid, since the big gold price boom of the late 2000s such a hypothesis is no longer consistent. In fact, gold is now probably the most prevalent commodity recovered via AM; its price has increased by more than 560% since 1997, when Veiga first wrote his assertion.

Nowadays, even inefficient operations characterized by very low production can justify the initial investment in underground mining equipment, with the recent price of gold making such activities profitable. In Latin America, many artisanal mines currently exploit underground deposits; they generally use basic underground equipment to drill and blast along quartz veins, but their technological awareness is scarce and their geological knowledge close to zero. This is the reality that must be dealt with.

A number of organizations around the world are now beginning to conduct formal research examining AM (such as INIGEMM in Ecuador and the USP Center for Responsible Mining in Brazil). An aspect of these projects involves the creation of a mapped census and the standardized characterization of existing operations. As underground AM is essentially a novelty of the last few years, scientific literature on the subject is practically non-existent (at least at the time of writing).

The present chapter generated itself spontaneously after the extensive work performed on field during this doctoral research. The aim of this chapter is to establish basic indicators which are easy to determine during preliminary field visits, and which can be used as a basis on which to characterize small-scale and/or artisanal mines in a standardized manner.

The purpose of these indicators is to contribute to an international database aimed at:

1. Creating a statistical base for research on artisanal and small-scale mining.
2. Comparing in an objective manner the technical characteristics and potential for sustainability of mines located in different regions of the world.
3. Quantitatively measuring the effects of improvement measures made over the years.

4.1 Methodology: Identifying the basic indicators

Sousa and Veiga (2009) already applied the indicators approach to evaluate effectiveness of improvement in AM: they used performance indicators to evaluate the effectiveness of training programs for Artisanal Miners. The authors consider that the indicators “should be:

- *pertinent*, in that it should represent well the phenomenon being studied;
- *operational*, in the sense that it is easily understandable, collectable, and measurable;
- *accumulative*, such that it can be related to other indicators to showevidence and trends;
- *economically appraisable*, in the sense that it can be related to impacts on costs”

This study addresses the issue in a different way: the basic indicators proposed here need to be able to characterize AM and indicate their potential for upgrade to sustainable SSM units. For this purpose, in order to be effective, the basic indicators must conform to the following different requirements:

1. To be easily recordable during a short field visit. Data should be provided by the miners or be accessible via simple observation, with quick field tests performed using portable equipment. Historical data should be avoided if they cannot be double-checked. The use of complex instrumentation should also be avoided at the preliminary stage due to the difficulty of transport to remote locations.

2. To be quantitative whenever possible, in order to avoid imprecision and subjective interpretation. The indicators should be as independent as possible from the subjectivity of the operator recording the data.

3. To be able to measure the specific characteristics of artisanal mines that distinguish them from conventional mining activities. Certain indicators must therefore be able to describe the potential sustainability of the operation.

These basic indicators must act as “indicators of sustainability”, providing an indication of the potential of an AM operation to be upgraded to an industrial SSM unit.

4.2 Results: Identification of basic indicators

The following list of indicators is elaborated on the combined basis of the above-mentioned requisites and the experience of the authors during field inspection of South American small-scale mines. The indicators are sorted by theme and are accompanied by general instructions as to how to detect the appropriate data in the field. In order to simplify their graphical exposition, the indicators are organized as follows:

- The following paragraphs contain a general discussion regarding the choice of the indicators.

- At the end of the chapter a complete list of the indicators is presented, structured in a suggested standardized record format specifically designed for use during field inspection.

General information

The purpose of this set of data is to unambiguously identify the mine, its ownership and concessionaire. The data to be provided must include the mine's location in terms of GPS coordinates and political geography, with other site indicators defining the transport infrastructure, access to basic services and any governmental presence in the territory. These indicators not only characterize the economic viability of the mine, but also its operational health and safety (OHS) conditions.

Geological and geotechnical indicators

This group of indicators includes geo-structural and geotechnical parameters influencing the utilized mining methods and excavation techniques, and therefore also the mine's OHS status. It does not include geochemical factors associated with mineral grades that require more complex analysis to be determined; these must therefore be included in the phase of detailed characterization instead of the preliminary investigation. As AM is generally characterized by a lack of geological exploration, the best way to collect such data is direct observation inside the mine. Further information, especially the one related to the experience gained from past operations, can be collected via miner interviews; however, this information must always be double-checked in order to avoid data bias due to subjective evaluation. Interviews with miners are a good tool with which to perceive their degree of knowledge regarding local geology (lithotypes, bedding planes, presence and location of faults and geological contacts), which in turn acts as an indicator of their rational use of the mineral resource. Literature research is also often a good tool, especially in areas where mining activities have been conducted for extensive periods in the past (AM is often established in areas abandoned by conventional mining companies). Three subsets of geological indicators should be collected:

- *Geological indicators*

  Geological survey is rarely performed in AM before the opening of the mine, and thus the shape of the orebody is frequently unknown to the miners, who also use production excavations as a means of geological exploration. Although only outcrops and mining faces are accessible in terms of preliminary geological exploration, it is usually possible to obtain basic information regarding the orebody and embedding rock in terms of their lithology, geology, hydrology and mineralogy.

- *Geotechnical indicators*

  The geotechnical indicators to be collected are the same as those for conventional mining or tunneling activities: characteristics of the intact rock (both ore and embedding rock), fracture systems and the presence of groundwater. For basic characterization it is important to focus on data representative of the characteristics of the mine and those that can be easily measured during a preliminary field visit with simple portable instruments such as a geotechnical compass, measuring tape, geological hammer, and Schmidt's hammer (on first approximation the latter's rebound can be correlated to UCS range classes). Many of the proposed indicators are classified based on the widely used RMR classification (Bieniawski, 1989). An extensive description of the methodology for data collection is provided by the IRSM (1981) and can be found in many classic manuals (such as Hoek et al., 1997 or Wyllie and Mah, 2004, amongst others).

- *Ground support indicators*

  Artisanal mining is often an irrational activity. This is broadly reflected in the employed ground support, which is frequently installed only when danger is directly perceived. While certain data must be provided, including a description of ground support structures and their status, other indicators should also be included in order to characterize (indirectly) the miners' degree of awareness regarding the need for rock support. This includes evidence of scaling operations, the presence of large-span unsupported stopes and evidence of pillar robbing.

Operational indicators

Operational indicators describe the employed mining methods and their efficiency; obtained field data must include a general description of the mining method and techniques. A list of the equipment present in the mine will also give an idea as to the latter's degree of mechanization; data recorded should include equipment age, the quality of maintenance, and the presence of eventually hazardous artisanal customization.

Mining efficiency can be evaluated both in terms of single tasks and as part of a global overview. In order to obtain an estimation of the global efficiency of a mining operation, an effective indicator is the tonnage of ore produced daily per capita of miners (Equation 12).

$$\text{tpc} = \frac{P}{w \times N} \qquad \left[\frac{t}{man \times day}\right] \tag{12}$$

Where *tpc* = tonnage per capita [t]; *P* = ore production in one day [t]; *w* = number of workers per shift [-]; *N* = number of shifts/day.

The efficiency of individual tasks is also particularly important, as it reflects the degree of artisanality of the mining operation. The efficiency of drilling and blasting operations can be easily evaluated by calculating the pull efficiency (Equation 13), and comparing the Powder Factor and Specific Drilling value of the blast with values commonly adopted in conventional mining for tunnels with the same characteristics.

$$\eta = \frac{L_t - \overline{L_r}}{L_t} \times 100 \tag{13}$$

Where L_t= total drilled length and $\overline{L_r}$= average remaining hole depth on the tunnel face. The first term can be obtained by measuring the length of drilling rods, by supervising drilling operations or via interviews with drilling operators regarding the drilled length. The second term is easily obtainable by inserting a folding rule or semi-rigid measuring tape into the bottom of the holes.

The presence of competent and trained workers is not only a requisite for the success of every enterprise, but also has an impact on the potential for sustainability. The number and assignment of miners must therefore be recorded, including an indication of those who have received some kind of mining training. In addition, it is equally important to census the number and function of employees not directly involved in mining activities (such as maintainers, administrative employees, technicians, cooks, handymen), as this information provides an indication of livelihoods in the mining area.

Indicators of explosives handling and storage

Explosives are diffusely employed in artisanal underground mining, with the misuse of explosive material considered one of the most common causes of significant accidents.

In artisanal mines, explosives are often obtained via smuggling, impacting both on mining cost due to their higher price and on operational safety because they are often employed past their expiry date. As the explosives used in many mines are handcrafted, they are often associated with evident safety and efficiency problems; a complete list of safety rules for the handling of explosives is available in ISEE (2011). During preliminary mine characterization, the type and manufacturer of the explosives and initiation devices must be recorded, whilst it should also be observed whether the explosive material is properly stored, transported and handled. A fundamental component of these observations is to check whether the explosives and initiation devices are suitable for the specific operating conditions of the mine in question.

Indicators of OHS

The risk management methods employed in conventional mining are not implemented in artisanal mines due to their severe complexity. The scarce literature available regarding OHS in AM tends to adopt a simple prescriptive approach, defining certain simple safety rules that miners should follow in order to reach a minimum acceptable safety level (Walles and Jennings, 2001; Walles, 2007). For preliminary characterization, critical indicators should be investigated as a priority, referring both to the global structure of the mine and to the job conditions during individual operations. The list of critical OHS factors is based on the main sources of hazard and accidents in SSM reported by Hentschel et al. (2002), and on the list of main hazards generally present in mining created by Donoghue (2004). In terms of their general organization, the main OHS indicators include access to sanitary personnel and structures in case of emergency, the presence of personnel trained in safety practices and the existence of some form of risk management system such as an accident record book. It is important to check for the existence of accident insurance for the workers, while the availability and use of personal protective equipment (PPE) must also be recorded. Even if the PPE utilized is at the lower end of the risk control hierarchy (OHS, 2011), its presence can be taken as strong evidence of miners' awareness of OHS issues.

Care must be taken to record the state of entrance and shaft protection, as these areas are frequently where accidents originate due to falls or rockfall. As movement conditions in artisanal mines are often prohibitive, it must be recorded whether it is possible to walk upright, as well as the condition of the floor surface. Climbing on ropes and/or shaft structures is common practice in artisanal mining; the vertical movement of personnel must therefore also be described.

Environmental indicators

- *Inside the Mine*

  The basic indicators of environmental quality in an underground artisanal mine must be those which provide a simple description of ventilation and air quality, including an assessment of the ventilation system using qualitative air parameter values. The density of dust clouds and fumes in a tunnel can be qualitatively evaluated by observing the cone of a flashlight. Oxygen levels are roughly measurable via the use of a flame (candle or lighter), using the condition of the same flame outside the mine as a reference. At very low oxygen levels (O_2 about 16%) the flame will be extinguished and impossible to light again. Such low oxygen content is well below any level of safety; in this case exploration must be interrupted immediately and anyone present must return to the open air.
- *Mine Surroundings*

  A distinction must be made between artisanal mines and artisanal processing plants. The majority of environmental damage generally attributed to artisanal mining originates at the treatment facilities, due to the employment of hazardous chemicals such as mercury and cyanide; the mine itself represents a low source of large-scale environmental hazard. Hazards associated with the environment around artisanal mines are generally related to water, air, land system and waste. Basic indicators must include the destination of outflow water, whilst any suspicion of acid drainage should also be checked, as should the diffusion of dust, smoke and fumes outside the mine. Floral damage such as the unusual presence of dry plants and grass in a specific area can indicate the deviation of groundwater due to the mining excavations. Waste disposal is always neglected by artisanal miners; evidence of rock fall hazard and acid drainage from waste material must therefore be investigated, especially if directed towards third party property.

Indicators of the legal status

In AM, the degree of formalization of the operation and working relationships varies greatly depending on the company, region and local legislation. The evaluation of mine formalization is essential in order to assess the latter's potential sustainability, not only granting easier access to external capital and markets, but also protecting the miners from government sanctions and allowing governments to regularly collect taxes and royalties. As formalization and tax payment is a very sensitive topic in certain regions, information provided by the miners should always be double-checked by examining legal documents confirming the assertions made. For any legal document examined, it is essential that photographic evidence is also taken and attached to the report as a control technique. The working relationship amongst individual miners and between the miners and the concessionaire of the AM activities is a source of uncountable solutions encountered in many countries. The legal status of such relationships must be documented and the main terms of association described. Furthermore, since child labor is an unfortunate occurrence in some artisanal mines, any evidence should be noted and generally described.

4.3 Answering the question: HOW CAN SSM BE EVALUATED AS SUSTAINABLE?

The basic indicators listed in the present work have been specifically individuated to measure the peculiar characteristics of underground artisanal mines which differentiate the latter from industrial mines. The purpose of these indicators is the standardization of artisanal mine evaluation on a quantitative basis, an important yet currently unavailable research tool. The data collection forms here reported are designed to be easily used by researchers during short field visits. Since researchers investigating artisanal mining often possess different technological and scientific backgrounds (the most common being mining, metallurgy, geology and hydrology), users must be properly trained in the compilation of each item found on the forms before the latter are put into operation. Literature references for this purpose can be found below. The indicators collected during field visits are intended to contribute to the establishment of standardized artisanal mining databases, thus creating the possibility for subsequent statistical analysis, and more importantly, quantitative evaluation of improvement measures taken over the years. As discussed above, the analysis of such indicators enables the potential sustainability of an underground artisanal mine to be measured, as well as its upgrade over time towards classification as an industrial underground small-scale mining unit.

Acknowledgements

Many thanks to Lorenzo Magny, who helped a lot in the identification of basic indicators.

<table>
<tr><th colspan="4"><u>GENERAL INFORMATION</u></th></tr>
<tr><td colspan="2">Name of mine</td><td colspan="2"></td></tr>
<tr><td colspan="2">Municipality</td><td colspan="2"></td></tr>
<tr><td colspan="2">Province/Region/State</td><td colspan="2"></td></tr>
<tr><td colspan="2">Country</td><td colspan="2"></td></tr>
<tr><td colspan="2">Mine Ownership
(legal name)</td><td colspan="2"></td></tr>
<tr><td colspan="2">Mineral Concession
(type and number)</td><td colspan="2"></td></tr>
<tr><td colspan="2" rowspan="2">COORDINATES</td><td>SYSTEM</td><td>e.g. Lat/Long, UTM, UPS</td></tr>
<tr><td>MEASUREMENTS</td><td></td></tr>
<tr><td rowspan="8">SITE INDICATORS</td><td>Water Supply
(capacity)</td><td colspan="2"></td></tr>
<tr><td>Electric Supply
(Voltage, phases)</td><td colspan="2"></td></tr>
<tr><td colspan="3">TRANSPORT INFRASTRUCTURE</td></tr>
<tr><td colspan="3">Type of roads, condition, seasonality</td></tr>
<tr><td colspan="3">BASIC SERVICES</td></tr>
<tr><td colspan="3">health structures, food and lodging, public transport</td></tr>
<tr><td colspan="3">GOVERNMENTAL PRESENCE</td></tr>
<tr><td colspan="3">police enforcement, security conditions, schools</td></tr>
<tr><td rowspan="2">HISTORICAL RECORD</td><td colspan="3">EXISTENCE OF HISTORICAL RECORD</td></tr>
<tr><td colspan="3">Describe any type of historical record present in the mine (regarding production, accidents, consumption)</td></tr>
</table>

GEOLOGICAL AND GEOTECHNICAL INFORMATION										
GEOLOGY										
	OREBODY					WASTE ROCK				
LITHOTYPE										
TYPE OF DEPOSIT										
OVERALL SHAPE AND DIRECTION										
MINERALOGY										
WATERTABLE (seasonal positions)										
GROUNDWATER INFLOW	*Completely dry*		*Damp*		*Wet*		*Dripping*		*Flowing*	
MAIN SETS OF DISCONTINUITIES										
	OREBODY					WASTE ROCK				
Spacing of discontinuities	*> 200 cm*	*60 - 200 cm*	*20 - 60 cm*	*6 - 20 cm*	*< 6 cm*	*> 200 cm*	*60 - 200 cm*	*20 - 60 cm*	*6 - 20 cm*	*< 6 cm*
Condition of discontinuities	Very rough, Not continuous closed, Unweathered	Slightly rough, Separation < 1 mm Slightly weathered	Slightly rough surfaces Separation < 1 mm Highly weathered	Slickensided, Separation 1-5 mm Continuous	Separation > 5 mm Continuous	Very rough, Not continuous closed, Unweathered	Slightly rough, Separation < 1 mm Slightly weathered	Slightly rough surfaces Separation < 1 mm Highly weathered	Slickensided, Separation 1-5 mm Continuous	Separation > 5 mm Continuous
Average UCS	*< 25 MPa*	*25 - 50 MPa*	*50 - 100 MPa*	*100-250 MPa*	*> 250 MPa*	*< 25 MPa*	*25 - 50 MPa*	*50 - 100 MPa*	*100-250 MPa*	*> 250 MPa*
TENSION CRACKS	*none*		*scarce*		*occasional*		*frequent*		*systematic*	
UNSTABLE WEDGES	*none*		*scarce*		*occasional*		*frequent*		*systematic*	
GROUND SUPPORT										
Type of ground support structures										
Materials used for ground supports										
Condition of ground supports										
Evidence of scaling operation	*none*		*scarce*		*occasional*		*frequent*		*systematic*	
Unsupported stopes	*none*		*scarce*		*occasional*		*frequent*		*systematic*	
Evidence of Pillar Robbing	*none*		*scarce*		*occasional*		*frequent*		*systematic*	

<table>
<tr><th colspan="7"><u>OPERATION</u></th></tr>
<tr><td>Geological control of operation</td><td>None</td><td colspan="2">Visual on outcrops and mining faces</td><td>From production drilling</td><td>Sampling</td><td>Exploratory drilling</td></tr>
<tr><td rowspan="6">MINING METHOD</td><td colspan="6">MINING METHOD (or methods if more than one is adopted)</td></tr>
<tr><td colspan="6"></td></tr>
<tr><td colspan="6">EXCAVATION TECHNIQUE (mechanic, drill and blast, manual, combined)</td></tr>
<tr><td colspan="6"></td></tr>
<tr><td colspan="6">MUCKING and HAULAGE SYSTEMS (vertical and horizontal)</td></tr>
<tr><td colspan="6"></td></tr>
<tr><td>EQUIPMENT</td><td colspan="6">A list of the equipment present in the mine, indicating its obsolescence, the quality of maintenance and eventual hazardous artisanal customizations</td></tr>
<tr><td rowspan="4">PERSONNELL</td><td colspan="6">MINERS (number and assignment; indicate those who received professional training)</td></tr>
<tr><td colspan="6"></td></tr>
<tr><td colspan="6">EMPLOYEES (not directly involved in the mining activity such as maintainers, administrative employees, technicians, cooks, handymen)</td></tr>
<tr><td colspan="6"></td></tr>
<tr><td rowspan="3">MINING EFFICIENCY</td><td colspan="2">P Ore production in one day [t]</td><td colspan="2"></td><td rowspan="3">tpc</td><td rowspan="3">$\text{tpc} = \frac{P}{w \times N}$</td></tr>
<tr><td colspan="2">w Number of workers per shift</td><td colspan="2"></td></tr>
<tr><td colspan="2">N Number of shifts/day</td><td colspan="2"></td></tr>
<tr><td rowspan="3">BLASTING EFFICIENCY</td><td colspan="2">Lt total drilled lenght</td><td colspan="2"></td><td rowspan="2">η</td><td rowspan="2">$\eta = \frac{L_t - \overline{L_r}}{L_t}$ x 100</td></tr>
<tr><td colspan="2">Lr av. depth of the remaining bottom of the holes</td><td colspan="2"></td></tr>
<tr><td>Q Total charge per round [kg]</td><td></td><td>S Face Section [m^3]</td><td></td><td>P.F. [kg/m3]</td><td>$P.F. = \frac{Q}{S \cdot L_t}$</td></tr>
</table>

<table>
<tr><th colspan="9"><u>EXPLOSIVES HANDLING AND STORAGE</u></th></tr>
<tr><td rowspan="4">EXPLOSIVES</td><td rowspan="2">MAIN EXPLOSIVE</td><td>Type</td><td>NGL-based</td><td>AN-based (bulk)</td><td>AN-based (cartridge)</td><td>Emulsion (bulk)</td><td>Emulsion (cartridge)</td><td>Other</td></tr>
<tr><td>Manufacturer (specify whether artisanal)</td><td colspan="3"></td><td colspan="2">Within expiration date (YES or NO)</td><td></td></tr>
<tr><td rowspan="2">SECONDARY EXPLOSIVE (Booster or special applications)</td><td>Type</td><td>NGL-based</td><td>AN-based (bulk)</td><td>AN-based (cartridge)</td><td>Emulsion (bulk)</td><td>Emulsion (cartridge)</td><td>Other</td></tr>
<tr><td>Manufacturer (specify whether artisanal)</td><td colspan="3"></td><td colspan="2">Within expiration date (YES or NO)</td><td></td></tr>
<tr><td rowspan="4">INITIATION DEVICES</td><td rowspan="2">IN-HOLE INITIATION (PRIMING)</td><td>Type</td><td>Fire cap + safety fuse</td><td>Non-electric</td><td>Electric</td><td colspan="2">Det. cord as priming device</td><td>Other</td></tr>
<tr><td>Manufacturer</td><td colspan="3"></td><td colspan="2">Within expiration date (YES or NO)</td><td></td></tr>
<tr><td rowspan="2">HOLE-TO-HOLE DELAY</td><td>Type</td><td>Safety fuse</td><td>Non-electric</td><td>Electric</td><td>Det. cord relay</td><td>Other</td><td>No delays</td></tr>
<tr><td>Manufacturer</td><td colspan="3"></td><td colspan="2">Within expiration date (YES or NO)</td><td></td></tr>
<tr><td colspan="9">PROPER TRANSPORT of explosive material</td></tr>
<tr><td colspan="9">e.g. blasting caps and explosive transported separately</td></tr>
<tr><td colspan="9">PROPER STORAGE of explosive material</td></tr>
<tr><td colspan="9">e.g. blasting caps and initiating devices stored separately, safe and dry storage rooms, protection against accidental explosion</td></tr>
<tr><td colspan="9">SUITABLE INITIATION SYSTEM</td></tr>
<tr><td colspan="9">e.g. safety fuse must be kept away from presence of water, and electric initiation to take place away from water and metallic ore</td></tr>
<tr><td colspan="9">SUITABLE EXPLOSIVES</td></tr>
<tr><td colspan="9">e.g. ANFO and granulate nitrate explosives often have a negative oxygen balance</td></tr>
<tr><td colspan="9">SAFE CHARGING PROCEDURE</td></tr>
<tr><td colspan="9">e.g. primed cartridges must not be stomped upon, charging must be done after and not during perforation</td></tr>
</table>

]

<table>
<tr><td colspan="9"><u>OPERATIONAL SAFETY AND HEALTH</u></td></tr>
<tr><td rowspan="2">ORGANI-ZATION</td><td colspan="2">Access to an occupational doctor</td><td colspan="2">Presence of a safety supervisor</td><td colspan="2">Presence of an accident recording system</td><td colspan="2">Existence of a risk management system</td></tr>
<tr><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td rowspan="2">FIRST AID</td><td colspan="2">Availability of first-aid equipment</td><td colspan="2">Presence of personnel trained in first aid</td><td colspan="2">Access to health care structures</td><td colspan="2">Accident insurance for personnel</td></tr>
<tr><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td rowspan="3">PPE (Personal Protection Equipment)</td><td colspan="3">Percentage of workers wearing PPE as common practice</td><td colspan="5"></td></tr>
<tr><td colspan="8">LIST OF PPE EMPLOYED (Type of PPE and suitability for each task)</td></tr>
<tr><td colspan="8"></td></tr>
<tr><td rowspan="10">Mine Structure</td><td rowspan="3">MINE PORTAL</td><td colspan="2">Protected (describe)</td><td colspan="5"></td></tr>
<tr><td colspan="2">Unprotected (describe)</td><td colspan="5"></td></tr>
<tr><td colspan="2">Section (width x height)</td><td colspan="5"></td></tr>
<tr><td rowspan="3">TUNNELS AND ADITS</td><td colspan="2">Section (width x height)</td><td colspan="5"></td></tr>
<tr><td colspan="2">Ease of movement</td><td>Normal</td><td colspan="2">Difficult</td><td colspan="2">Crawling</td></tr>
<tr><td colspan="2">Floor condition</td><td>Protected (boards or other)</td><td>Dry</td><td>Muddy</td><td>Still water</td><td>Running water</td></tr>
<tr><td rowspan="4">SHAFTS</td><td colspan="2">Protected (describe)</td><td colspan="5"></td></tr>
<tr><td colspan="2">Unprotected (describe)</td><td colspan="5"></td></tr>
<tr><td colspan="2">Section (width x height)</td><td colspan="5"></td></tr>
<tr><td colspan="2">Access method</td><td>Stair</td><td>Rope</td><td>Climb on supports</td><td>Free climb</td><td>Shafts not used for transport</td></tr>
</table>

ENVIRONMENTAL CONDITIONS INSIDE MINE						
VENTILATION	Ventilation system	*None*	*Natural*	*Compressed air*	*Fan + hose*	*Mixed*
	Direction of air flow (if present)	*Blow (push)*		*Aspirating (pull)*		*Both*
	Type of fan (if employed)	*Artisanal fan*		*Industrial fan*		*Fan designed for mining purposes*
	Hours of ventilation (per shift and per day)					
AIR QUALITY	Air temperature	*Freezing*	*Cold*	*Normal*	*Hot*	*Extremely hot*
	Humidity	*Extremely dry*	*Dry*	*Normal*	*Humid*	*Extremely Humid*
	Presence of dust and fumes	*None*	*Diffuse dust (visible in Flashlight)*	*Concentrated dust (visibility reduced, cone of the flashlight is clearly visible)*		*Compact dust cloud (visibility impeded, cone of flashlight cannot penetrate dust cloud)*
	Oxygen levels (When low, exploration must be interrupted immediately and anyone present must return to the open air)	*Normal (O_2 about 21%)*		*Low (O_2 about 19%: flame height is reduced to a half that of outside)*		*Very low (O_2 about 16%: flame extinguished and is impossible to light again.*
ENVIRONMENTAL CONDITION OF MINE SURROUNDINGS						
WATER	First destination of outflow of underground water	*decantation pools*	*direct into watercourse*	*drainage into the ground*	*Other (specify)*	
	Unnatural color of water (specify)	*This is a potential indicator of acid drainage*				
	Presence of sediments and salinity in the water					
AIR	Diffusion of dust, smoke and fumes outside mine portal					
LAND and ENVIRONMENT	Evidence of ground subsidence					
	Evidence of flora damage	*e.g. such as unusual presence of dry plants and grass in a specific area*				
WASTE DISPOSAL	Sterile piles	*Dedicated area, on flat land*		*Dedicated area, on slope*		*Irregularly dispersed around mining area*
	Rock fall hazard from piles	*None*		*Hazard inside mine area*		*High, on third party property*
	Presence of drainage system (describe)					

<table>
<tr><th colspan="8"><u>LEGAL STATUS</u></th></tr>
<tr><td rowspan="3">AREA</td><td>Legal status of mining concession</td><td colspan="6"></td></tr>
<tr><td>Ownership of area</td><td colspan="6"></td></tr>
<tr><td>Fruition of area</td><td>Irregular</td><td>By concession</td><td>Mineral exploration permit</td><td>Other (specify)</td><td colspan="2"></td></tr>
<tr><td rowspan="6">OWNERSHIP AND WORK RELATIONSHIPS</td><td rowspan="2">Work relationship between concessionaire and miners</td><td>Land is free of concession</td><td>Miners are themselves the concession-aires</td><td>Miners work for the concessionaire</td><td>Miners are in partnership or other form of profit sharing system</td><td>Miners operate in conflict with the concession-aire</td><td>Other (specify)</td></tr>
<tr><td colspan="6">Specify the work relationship between miners and concessionaire</td></tr>
<tr><td rowspan="2">Legal status of ownership</td><td>None</td><td>Company ownership</td><td>Company of partners</td><td>Company of shareholders</td><td>Cooperative</td><td>Other (specify)</td></tr>
<tr><td colspan="6">Specify form of ownership</td></tr>
<tr><td>Child Labor</td><td colspan="6">Describe any evidence of child labor</td></tr>
<tr><td>Main terms of contract, article of association or statute</td><td colspan="6"></td></tr>
<tr><td rowspan="16">COMPLIANCY WITH PERMITS AND TAXES</td><td colspan="7">Existing Documentation of National mining authorities</td></tr>
<tr><td>Document type</td><td colspan="2">Document no.</td><td colspan="2">Issue date</td><td colspan="2">Issuer</td></tr>
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<tr><td colspan="7">Environmental licensing</td></tr>
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<tr><td colspan="7">Documents proving payment of taxes and royalties</td></tr>
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</table>

PART 3 – HOW CAN BE SUSTAINABLE SSM PUT INTO PRACTICE?

5. CHAPTER 5 - CREATING A PRACTICAL APPROACH FOR THE MANAGEMENT OF RESOURCES AND RESERVES IN SMALL-SCALE MINING

After defining what sustainable mining is, addressing its assessment, and measuring its potential and impact, it is now time to individuate the most viable solution for SSM to a shift towards sustainable operations.

5.1 Introduction

The high investments associated with the installation of a mine requires the careful management of risks associated with the business (Singer and Kouda, 1999). This includes careful geological exploration research, detailed analysis, review and modeling of technical data on the indicated resources, and the study of alternative mining scenarios to exploit such resources in order to prove it as a reserve. An example of the process of "resource-to-reserve definition" can be found in Diering et al. (2013):

1) Reserves are based on a scheduled resource, ensuring that the planning discipline is integral to process

2) Appropriate mine design and layouts are applied to the resource areas as dictated by current mining methods and mine design criteria to derive a mineable resource

3) The mineable resource is scheduled according to production requirements to develop a scheduled resource

4) Only current operations (level 1), approved projects in execution (level 1e,) and projects in feasibility study (level 2a) included in the business plan are defined as reserves (in Proved and Probable categories according to SAMREC)

5) The remaining scheduled area of the Life of Mine (LOM) plan is termed scheduled exclusive resource and includes projects from Level 2b, 2c, and Level 3 with the objective of optimally extracting the available resources

6) Resource categories have been increased to cater for exclusions and confidence levels (e.g. mineral resources above the geothermal gradient cut-off are moved to mineral inventory)

7) The introduction of mining losses pertaining to resources left in pillars. The mineable resource excludes material locked up in mine-design related pillars

8) Uneconomic production plan 'tails' revert to mineral resource or mineral inventory (depending on position in plan) through a 'tail management' process

9) The application of modifying factors (technical, mining, geotechnical, processing and recovery, legal, market, and social/government factors) is implemented in three distinct phases:

   i. Mine design and scheduling-Those modifying factors that impact on dilution of the resource (i.e. stope width versus resource width, tertiary development and other waste mining done on the reef horizon etc.) and modifying factors that define mining losses (i.e. non-mineable pillars and RIH/RIF mining inefficiencies etc.) are applied to the criteria included in establishing the mine design and scheduling

   ii. Processing - Those modifying factors that influence the efficiency of processing and recovery are applied to the scheduled resource, and the result is a mineable reserve

   iii. Economic - The subsequent application of modifying factors that influence the economic aspects of the mining operation results in the tail management requirement.

10) The scheduled reserves are multi-discipline peer-reviewed and signed off by the competent person(s)

All this process is required for the disclosure of mining projects, and is mandatory to adhere to reference standards such as the Australian JORC (2004), the South-African SAMREC (2009) or the Canadian NI 43-101 (2011). Nevertheless, all this initial preparation work is highly costly. While being largely diffused in a standardized manner in Large-Scale Mining, with large investments applied and state-of-the-art technologies employed, when dealing with Small-Scale Mining (SSM) the exploratory and modeling phases are generally neglected due to a lack of capital (Hruschka and Echavarría, 2011).

SSM "has had unprecedented growth in developing economies over the past few decades. AM is defined as the use of rudimentary processes to extract valuable minerals from primary and secondary ore bodies, and is characterized by the lack of long-term mine planning/control. It can be illegal or legal, formal or informal and can encompass everything from individual gold panners to medium-scale operations employing thousands of people" (Shena and Gunsonb, 2006). When approached as a business opportunity, SSM is quite critical: it is often related to poverty in remote areas, and is commonly seen as a problem due to its issues related to illegality and environmental pollution (Veiga 1997, 2006 and 2009, Shandro 2009, Spiegel 2010 Velasquez 2010). Nevertheless, Andrew (2003) highlights very clearly the positive potential of SSM: "Small-scale mining offers several potential benefits. It often allows the mining of otherwise uneconomic resources, since it is mobile, flexible, and requires little capital". This indicates that there is a positive return in overcoming the challenges related to SSM business. Seccatore et al. (2012) also indicate that "small-scale mining meets both the rapid customization with the necessities of the market and the technological and financial flexibility to adapt to the lower grades of the deposits to be exploited. These are all signals of a future development of small-scale mining in precious metals, especially gold, along the next decades". In the same study it is concluded that "efficiency in productivity is the main path to turn an AM unit into a sustainable and profitable Small-Scale industrial extractive unit". In SSM the greatest challenge to achieving this is the availability of initial capital investment (Hentschel et al., 2002, Hruschka and Echavarría, 2011). Because of the high risk of the operation, due to little guarantee of return and financial success, the SSM scenario, for investors, is in general less attractive and not very encouraging. This creates a condition similar to a "gambling" scenario for the operators of AM: with the limited economic resources available they invest directly in the operation, without previous geological exploration, restricting their operational planning on the available information, experience from previous operations and, often, simply on instinct. As Hruschka and Echavarría (2011) reported, "artisanal miners […] usually skip the exploration phase and […] proceed with extraction immediately after discovery". Such a lack of methodology creates the highest levels of uncertainty; hence a lack of credibility and a negative image for investors. A vicious circle is automatically triggered, a very common situation among SSM operators.

This chapter proposes a tool intended to "de-trigger" the vicious circle and manage the evaluation of resources and reserves for SSM operations in a sustainable manner.

5.2 A practical approach to assess the viability of small-scale mining

The main concept for approaching SSM in a sustainable way is the idea of converting an artisanal operation (AM) into a small-scale responsible enterprise. This can be done by providing technical knowledge, based on geological exploration, engineering, mineral processing and more efficient equipment. As the owner of an AM usually does not possess the necessary capital resources for such activities, the investment can be provided, through partnership, by an external investor.

The main differential of this new approach is to prove, during the early stages of the business, only a minimum mineral reserve that is able to return the investment committed to upgrading the AM into a small-scale industrial one. This is done in opposition to traditional large-scale mining exploration, consisting in performing a thorough exploration, with large financial investment and long-term planning. Like any activity in mineral exploration, at a large or small scale, the investment committed for reserve estimation is at high risk. Therefore, the proposal for SSM is to only invest what is absolutely necessary in the mineral exploration phase, and then cyclically replicate the minimum reserve approach exploration process, committing part of the proceeds from the sale of the produced mineral to prove the viability of the continued operation.

In the following paragraphs this concept is presented through a system of equations to determine the required minimal reserve, including an example with actual values from a small-scale underground mine in Ecuador.

5.3 Methodology

Geological exploration for large-scale mining follows the concept of high investment to prove the largest amount of reserves possible, in order to estimate the life-of-mine NPV of the project. The proposed methodology differs greatly from the traditional approach. It considers that SSM is characterized by quick installation, rapid payback and high flexibility, and uses these aspects as its keystones. It is based on the concepts of:

- "minimum reserve to be proved" and
- "replication".

The two concepts are explained below.

More detailed description of all the concepts developed in this section can be found in reference textbooks for Mining Engineering such as Hartman and Mutmansky (2002), Hustrulid and Bullock (2001).

For a given proven reserve base, the quantity of ore that is actually mined depends on the mining recovery. This can be lower than 1 when some portion of ore is left in place, or equal to 1 when all the ore reserves and presumably also part the embedding waste rock are mined. This is expressed in Equation 14, where V_R = Volume of proven reserves [m^3]; V_M = Volume of ore mined [m^3]; η_M = Mining Recovery ($\eta M \leq 1$)

$$V_M = V_R \cdot \eta_M \qquad (14)$$

When over-excavation occurs, the result is mining dilution of the run-of-mine (ROM) material, which has an impact on the resulting average grade of the ore mined. This is expressed in Equation 15, where g_M = average expected mining grade [g/t]; g_N = natural average mineral grade of the ore in place [g/t]; and η_D = Mining Dilution ($\eta_D \geq 1$), defined as the ratio of total amount of rock (ROM = embedding waste + ore) that is mined over the amount of ore extracted.

$$g_M = g_N / \eta_D \qquad (15)$$

After extraction, the ore has to be processed in order to recover the mineral of interest. The efficiency of this process is always lower than one, and the recovered metal amount in the concentrates is always less than the metal content of the mined-out material. This is expressed in Equation 16, where q_M = metal content in the concentrates [g]; q_R = metal contents of the ROM material [g]; and η_R = Processing Recovery ($\eta_R < 1$)

$$\eta_R = q_R / q_M \qquad (16)$$

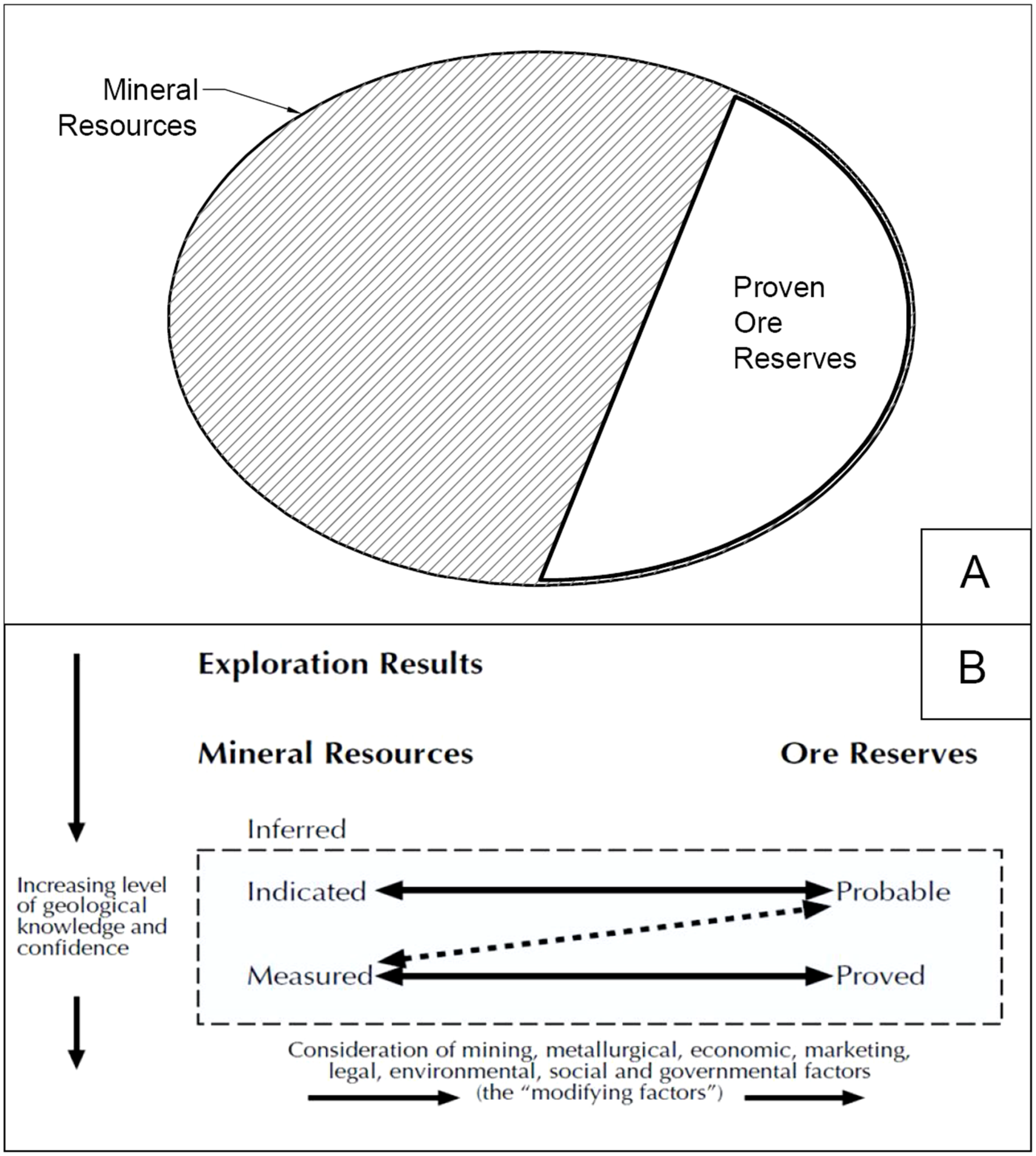

Figure 32 - Mineral resources and ore reserves: proven ore reserves as a subset of the mineral reserves (A); and general relationships according to the Australian Code JORC (2004) (B)

When a resource is qualified as indicated, in traditional large-scale mining capital is invested to characterize part of it as measured resources, and then mine planning and engineering studies are conducted to characterize the measured volume as proven reserves (***Figure 32***). The value of the proven reserves depends, amongst other factors, on the costs of geological exploration in order to prove the reserve, and the fixed capital costs (the so-called CAPEX) to start up the mining operation (part of the "modifying factors" as defined by JORC, 2004).

As specified in the introduction, in SSM the base assumption is the lack of capital for geological exploration at the local scale, and therefore the required investment has to be made available by an external investor. As experience has shown, it is extremely hard to encounter someone who is willing to invest into a costly exploratory campaign in a high-risk environment such as SSM. On the other hand, a small-scale investment able to prove and then consequently recover a reserve over a short term, obtaining a rapid payback, is the kind of financial operation an investor is likely to undertake (Hentschel et al., 2002). Therefore, in SSM the capital cost of exploration cannot be separated from the start-up costs. The costs of exploration must be embedded in a small-scale "package" of capital investment that allows the characterization of the minimum reserve to be proved, immediately followed by planning, start-up, production, recovery and sale of the product. As discussed below, the payback for such an operation may be as short as one year.

The value of the initial capital investment is calculated according to Equation 17, where IC = initial capital investment [$]; CE = unitary cost of exploration [$/m^3]; and OF = orebody factor. The fixed investments depend on the required productivity Pr [m^3/day] (that determines the size and choice of the equipment, as expressed in Equation 5), and are: M = equipment; S = infrastructures; P = plant; V = services; E = engineering; MO = mine opening; MD = mine development (defined as all the operations that allow access to the ore without directly mining into it).

$$IC = M + S + P + V + E + MO + MD + CE \cdot OF \cdot V_R \qquad (17)$$

$$(M, S, P, V, E) = f\,(Pr) \qquad (18)$$

In Equation 17, OF (orebody factor) is a very important component. It considers the shape and position of the orebody, and can be defined as an average ratio between the explored volume and the actual volume of the proven reserves. For instance, a mineralization in narrow vein, a typical occurrence for epithermal gold, will have a much higher OF than a diffused mineralization, such as alluvial or sedimentary gold deposits. This factor is empirical, depending on the shape and position of the orebody and its accessibility for geological exploration. It should be estimated on a case-by-case basis according to the available geological information. Its value is 1 for a perfectly diffused orebody that is directly accessible, and can reach values in the order of hundreds for narrow veins only accessible from far exploration points.

The relationship between the elements of Equation 18 is not linear amongst all the components. Due to production scale and technical issues, only each component of the first term (M, S, P, V, E) can be linked to productivity (Pr) through a single specific correlation that takes into account the mechanical properties of the specific equipment and the characteristics of the rock and ore to be mined and processed.

When both mine and plant are started up, the cost of the operation is characterized by the unitary costs of each phase of the recovery process, composing the so-called OPEX. Such costs are in general: CM = unitary cost of mining [$\$/m^3$]; CP = unitary cost of processing [$\$/m^3$]; and CA = unitary additional costs [$\$/m^3$]. The income of the operation depends on the price of the mineral product on the market: where p = price of the mineral product [$/g]. Such gross income can be defined as the revenues from the selling of the recovered mineral minus the operating costs, as in Equation 19.

$$\text{Gross Income} = V_R \cdot (g_N / \eta_D) \cdot \eta_M \cdot \eta_R \cdot p - (CM + CP + CA + CE\ \ OF) \cdot (V_R \cdot \eta_M) \tag{19}$$

Looking from the investor's point of view, the required gross income for the mine to be efficient (therefore viable) can be defined as the one that returns the initial investments and produces a profit:

$$\text{Gross Income} = IC + PROFIT \tag{20}$$

The two expressions of Equations 19 and 20 can then be put together into Equation 21:

$$V_R \cdot (g_N / \eta_D) \cdot \eta_M \cdot \eta_R \cdot p - (CM + CP + CA + CE\ \ OF) \cdot (V_R \cdot \eta M) = M + S + P + V + E + MO + MD + CE \cdot V_R \cdot OF + PROFIT \tag{21}$$

Considering V_R as the unknown variable, and having all the unitary costs as constants, it is possible to calculate the minimum reserve to be proven to repay the initial investment and to provide the desired profits. Considering the limited availability of capital investment for SSM operations this is the bottleneck of every decision-making process throughout the sector. V_R can be calculated as in Equation 22.

$$V_{R,MIN} = \frac{\mathrm{M + S + P + V + E + MO + MD + PROFIT}}{\eta_M (g_N / \eta_D \cdot \eta_R \cdot p - C_M - C_P - C_A) - C_E \cdot OF} \tag{22}$$

It is very important to highlight that, at this stage of the research, taxes, financial costs, depreciation and inflation were not considered for the sake of simplicity in the discussion. Their introduction into the model will be the object of further dedicated studies.

As discussed above, the basis for a sustainable approach to SSM is a partnership between the mine owner and the external investor who provides the necessary initial investment. In this framework, PROFIT can here be divided into shares that will reflect the margins for the investor, for the mine owner and for further exploration to expand the proven reserve:

$$\mathrm{PROFIT} = P_{\mathrm{INVESTOR}} + P_{\mathrm{MINE\ OWNER}} + P_{\mathrm{FUTURE\ EXPLORATION}} \tag{23}$$

The margin to be dedicated to future exploration can be expressed as:

$$P_{\mathrm{FUTURE\ EXPLORATION}} = C_E \cdot OF \cdot V_{R2} \tag{24}$$

Where V_{R2} is the volume of the next portion of reserve to be proved. In this case, even if the mineral grade in the second volume V_{R2} was found to be too low for continuing the operation, no money would be lost in further exploration, and every stakeholder (investor and mine owner) gets out of the business with net profits.

Figure 33 illustrates the cyclical process of minimum-reserve exploration, production, and replication, which means further investment in geological exploration to expand the reserves and thus ensure further production. An option is when V_{R2} is defined by the “stakeholders” of the project, depending on the risk acceptable to the parties involved.

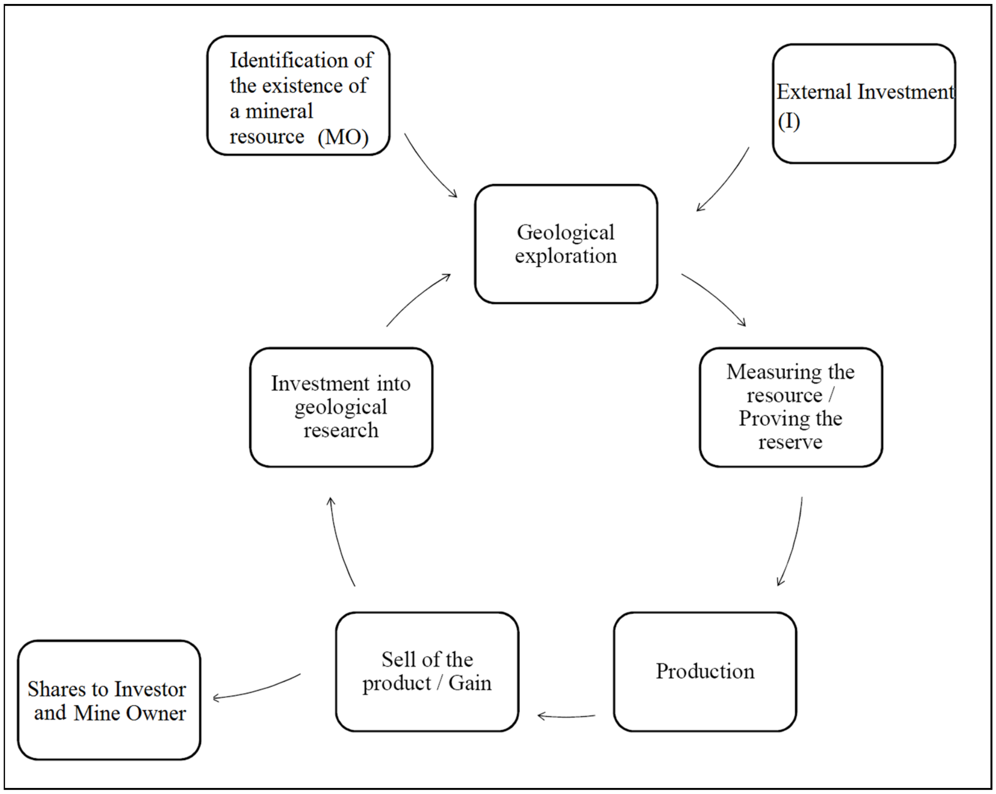

Figure 33 - Visualization of the concept of "replication" as a cycle, with identification of its stakeholders: Mine Owner and Investor. Depending on the size of the proven reserve it can be defined as the size of the mining operation and of the necessary investment.

5.4 **Example of Application**

The methodology described above has been applied to define the minimum reserve to be proved in a small-scale gold mine exploiting epithermal gold veins in Ecuador, where a development project is being carried on. The costs of mining and processing described below were estimated for a production rate of 200 t/d, with an expected average grade of 6 g/t. Both the mine and the plant are designed for such parameters.

The area

The mine is located close to the town of Portovelo, southern Ecuador, in the province of El Oro. This area has historically been dedicated to gold extraction since the pre-Columbian age (since the name "El Oro" means "The Gold"). The area of interest was industrially exploited by the USA-based SADCo Company from 1896 until the 1950s; later the property passed to a publicly-owned Ecuadorian company, and finally the mine closed in the 1980s. After the mine's closure, artisanal miners entered in the tunnels left by the mining companies in the area, in order to mine the small portions of the mineral veins left in place (Cortazar 2005, Cortazar and Lavanda 2008). In 1991, with the “Ley de Mineria” (Mining Law), the Ecuadorian government legalized small-scale mining activities, allowing the miners to move away from dangerous methods, providing access to technical national and international cooperation programs (COSUDE project, PRODEMINCA project amongst others) and attracting investors (Sandoval, 2001). The mine that is the object of this study is currently legally operating under Ecuadorian law as a small-scale mine. Due to this history, mining is socially accepted and actually a part of local culture in the Portovelo area as the main form of livelihood for the community (Cortazar 2005, Cortazar and Lavanda 2008). Skilled and trained workers are available amongst the local population. In the whole region are available power and water supply for industrial and mining purposes, adequate infrastructure and transportation and reliable retailers of any kind of small-scale mining equipment.

The stakeholders of the project

The mine owner (identified as “MO” in ***Figure 33***) and a Canadian-Brazilian joint-venture (investor, identified as “I” in ***Figure 33***) set up a new company to develop the current operation into a profitable small-scale mine (producing under 300 t/d according to the Ecuadorian Mining Law). The joint-venture decided to invest in the project based on the practical business-oriented approach presented in this paper. The new company, that will operate the mine according to industrial standards, aims to overcome the lack of capital that has prevented, up to now, proper planning and technical upgrade for the extension of the operation.

The new mining method

The mining method designed is an adaptation of “longhole sublevel stoping” for very narrow veins (see Stewart et al., 2011). In this method, adits are driven in sublevels inside the orebody along its horizontal direction, with connections between them and to the surface by a ramp. Panels are isolated between the adits, and are mined by means of long small-diameter blastholes. The blasted ore is hauled from the lower of two adits to the ramp, and subsequently transported to the surface.

The processing plant

The processing plant is designed to recover gold and copper using two different processes: gravimetry and flotation. Liberated gold particles are recovered using a gravimetric concentrator, intensive cyanidation and electro-winning to produce "doré" bars (see Veiga, 1997, Mostert 2005, Andreu et al. 2010). Un-liberated gold is recovered using flotation to produce a copper/gold concentrate. The terrain selected for the construction of the plant has morphology very adequate to host the tailings pond, which is designed according to the enforcing national laws and international standards. The cost of construction of the tailings dam and pond is embedded in the plant CAPEX, as shown in *Table **17***.

Costs variables

Detailed CAPEX and OPEX (Smith 2012, Ugwuegbu 2013) have been calculated for both the mine and the plant. Their main components are presented in Table 1. The costs of exploration are based on an integrated campaign of core drilling and geophysical investigation. All the variables of Eq. 22 are reported in *Table **17***.

Table 17 - Values of the variables used in the example of application

Variable	**Value**	**Unit**
M	1 935 832.44	USD
S	288 858.32	USD
P	2 829 154.48	USD
V	232 299.89	USD
E	864 707.30	USD
MO	216 737.02	USD
MD	132 180.75	USD
$PROFIT$	5 000 000.00	USD
η_M	0.8	
g_N	16.2	g/m³
η_D	1.2	
η_R	0.8	
p	54.16	USD/g
C_M	43.25	USD/m³
C_P	66.58	USD/m³
C_A	59.48	USD/m³
C_E	0.23	USD/m³
OF	30	

5.5 Results and discussion

With the given input values and the variables shown in Table 1, the minimum reserve to be proved $V_{R,min}$, calculated according to Equation 22, is 35,327 m³, with a grade of 16.2 g/m³, therefore with a gold content of 572 kg (about 18,200 oz). This is a simplified value, since, as said, is purposely not considering taxes, financial costs, depreciation and inflation for the sake of simplicity in the discussion. Nevertheless, the order of magnitude of the reserve is still very low. For a comparison, as reported by Schodde (2011), the smallest gold deposit estimated since 2008 by large-scale mining is the Bell Mountain (USA), consisting of 1.07 million ounces of Au (about 33.6 tons of Au). The volume that needs to be proved to make the operation viable, in terms of the order of magnitude, is 1/1000 in favor of the SSM operation.

5.6 Discussion on the challenges of the project of application

Many SSM operations in Latin America have been taken into account for the start-up of a pilot project based on the practical approach described in this paper. The main challenge to find the most suitable SSM unit for the pilot project was to overcome the barriers in the decision making process among the stakeholders, such as mutual trust, availability to negotiate and willingness to put an effort the start-up of the pilot project, along with large-scale geopolitical issues related to the countries where artisanal mining usually takes place.

Artisanal miners in Latin America are often organized in cooperatives (Sandoval 2001, Hentschel et al. 2002). It has been observed that, despite general willingness to develop a project to upgrade the artisanal operation into an efficient and responsible mine, the decision-making process among a cooperative is complex, often delayed, highly time and energy consuming. The experience of the authors in dealing with cooperatives of artisanal miners in Latin America has shown that on long-term positive results can be achieved, but the process can be slow. Such a delayed negotiation might discourage the stakeholders, if not properly dealt with and managed. Projects developed in SSM units owned by a single decision-maker are more likely to start up on a short term.

Therefore, the main selection criteria for the first pilot project were based on the easiness and readiness of the decision-making process more than on technical issues related to the deposit or the operation. Based on the same approach, other upgrade projects are expected to start up in the future as soon as negotiations come to an agreement between the stakeholders.

5.7 Answering the question: HOW CAN BE SUSTAINABLE SSM PUT INTO PRACTICE?

For a sustainable approach to SSM, it is necessary to create the conditions to turn artisanal mines into sustainable and profitable small-scale industrial extractive units. In order to do so a differential in the conception of geological exploration in the early stages of the business is proposed. Only a minimum mineral reserve has to be proved. This minimum reserve is the one able to return the investment committed to upgrading an existing AM into a small-scale industrial one.

The proposed approach to calculate this reserve contains two main concepts: a “minimum reserve” required for the project start-up, and “replication” to confirm the feasibility of continued operation.

The minimum reserve to be proved can be calculated considering the expense items contained in the CAPEX and OPEX of the mining business, together with the cost of geological exploration. The equation proposed to calculate this minimum reserve does not consider, at this stage of the research, taxes, financial costs, depreciation and inflation.

The proposed methodology has been applied to an actual underground gold mining operation, which has been chosen among many due to the readiness of the decision-making process to start up a pilot project. Actual data applied to the proposed model has shown that the reserves required for a small-scale operation are in the order of magnitude of 1/1000 of that required for large-scale mining, when both businesses possess the same level of feasibility.

4.8 Acknowledgments

I am very grateful to: Adriana Gonçalves, Francis Baker, Hernan Ruiz, Luan Parente, Olav Mejia and Tarik Haroon for their precious help in the quantification of capital costs and operational costs for the treatment plant.

Many thanks to Lorenzo Magny whose M.Sc. Thesis, that I co-supervised, has been the source for the quantification of capital costs and operational costs of the mine.

6 CHAPTER 6 – ASSESSING TECHNICAL AND OPERATIONAL ASPECTS OF TUNNEL ROUNDS IN ARTISANAL UNDERGROUND MINING

This chapter describes the activities and challenges of putting into practice the first step of the methodology described in Chapter 5: mineral exploration. Here are assessed the main technical and operational aspects of one of the main criticalities and sources of OHS hazard in underground SSM: tunnel blasting rounds. This chapter illustrates, with a practical example, that it is possible to achieve the modern requirements of quality, safety and productivity, while operating with mining equipment that basically possesses the same characteristics as that employed in the 1950s.

6.1 The mine

The mine where the assessment has been performed is the one described in Chapter 3 (Ecuadorian Mine), and to whom the entire Chapter 5 is dedicated.

The veins exploited in the mine are part of the Portovelo epithermal vein system. According to Van Thournout et al. (1996), the volcanic-hosted altered-mineralized system covers an area of more than 150 km2. More than 30 gold-bearing veins are identified up to now. They dip at angles of 45 to 70°, have lengths of hundreds of meters up to 2.5 km, and thickness of 0.8–1.5 m, in some places reaching 3–5 m (Vikentyev et al., 2005). In the mine object of this study, the embedding rock is a hard andesitic basalt, and two veins of economic value are intercepted. The mine is developed on a single level, the access to the ore body is provided by an adit (approximatively 2 x 2.5 m and 850 m long) connected to the veins by drifts driven alongside them. The JV manifested the interest to explore those tunnels and carry out core-drilling for the determination of mineral grade. It has been necessary, therefore, to perform underground blasts to open a 6 meter long tunnel to host the drilling machine. Since the drilling machine cannot be disassembled, in order to bring it in place it was necessary to demolish the massive concrete wall protecting the entrance and to stope blast over 25 sections of the adit in order to widen it. The MO provided the equipment and workforce to perform this preliminary excavation. This gave the operations its peculiar quality, having to achieve the modern requirements of quality, safety and productivity while operating with mining equipment that basically possesses the same characteristics as that employed in the 1950s.

Materials

The available equipment consisted of the following items.

Drilling equipment: A single pneumatic drill was available. It was a manually-handled model (***Figure 39***) with a rotary-percussive mechanism, using water as drilling fluid and sustained by a pneumatic jack. The only rods available had a length of 1.20 m or 1.60 m. The bits had a diameter of 1”1/2. The average drilling time for one blasthole was about 4–5 minutes.

Loading and hauling equipment: The loading equipment consisted of a single pneumatic loader (locally called *lampón*, see ***Figure 34***). The hauling equipment consisted of electric locomotors and few hauling wagons (*burras*, ***Figure 35***) which were unloaded by lateral tipping.

Figure 34 – Pneumatic loader (lampón)

Figure 35 - Hauling wagons "burras" (back) and electric locomotors (front).

Explosives: In the mine two kinds of explosives are used: *i*) Dynamite (NGL 80%) as booster and bottom charge, in cartridges of 1"1/8 x 8" (***Figure 36***); *ii*) Ammonium Nitrate (AN) explosive as column charge, in handmade paper cartridges (***Figure 37***).

Figure 36 – Cartridge of Dynamite already primed

Figure 37 -Ammonium Nitrate bag and empty newspaper cartridges. On the back is visible a bag of common AN fertilizer. (picture only available in b/w)

Due to the unavailability of other explosives and due to the experience of the workers in the use of these products, they were employed both for tunnel driving and for blasting the concrete door. The dynamite is industrially produced and is delivered to the mine already packed in cartridges. The nitrate explosive is common fertilizer, and is packed in handcrafted paper cartridges for ease of handling. It is composed of granular A.N. (34%N) without the addition of fuel oil. The F.O. was eliminated in the preparation of the charges when the miners empirically observed the consequences of the very negative oxygen balance of poorly mixed ANFO. In order to reduce the hazard of suffocation or air poisoning, ventilation shifts of 4 to 6 hours are left after each blast to ensure the evacuation of blasting fumes and the substitution of exhausted air.

It is still doubtful whether the ammonium nitrate has either the behavior of a detonating explosive or that of a deflagrating explosive under such conditions. According to dedicated studies (Oommen & Jain, 1999) it decomposes at around 230°C at a pressure of 760 mmHg, and above 325°C it deflagrates. The same authors note that, if confined, ammonium nitrate may detonate at between 260 and 300°C with a detonation velocity ranging between 1250 and 4650 m/s. Such VODs are close to the VOD values indicated by others authors for commercial ANFO (94% of A.N. and 6% F.O.), ranging between 2000 and 4400 m/s (Oloffson, 1988) and between 2400 to 4750 m/s (ISEE, 2011). According to the effective results in terms of fragmentation, it is possible to hypothesize the explosive behavior of the whole blasthole as follows: a) the primed dynamite works effectively as a high detonating charge, producing toe breakage and inducing shockwaves towards the collar that create primary cracking; b) the AN column works as a very loose detonating charge, producing secondary cracking and mainly opening the fractures and moving the pile by means of gas expansion. In order to assess the true behavior of the explosive it would at least be necessary to analyze the real composition of the product, because many accessory materials like chloride ions and heavy metals can catalyze the decomposition, modifying the performance of the explosion. Some field test should also be carried out in order to analyze the behavior of the product (VOD measurement) and the composition of the exhausted gases under the true operating conditions.

Ignition system

The dynamite cartridges are primed with a blasting cap, and ignited with a safety fuse. The blasting caps come already secured to 2 m of safety fuse and are inserted into the dynamite cartridge outside of the tunnel (***Figure 36***). This working method poses two main problems. The first is a safety problem since the cartridges are transported into the mine already primed (ISEE, 2001). The second problem is both a technical and a safety problem. Since the length of the fuse is fixed and is the same for all the mines, the precise timing of the firing pattern is practically impossible. The fuses are lit with a lantern (***Figure 41***), and the firing sequence depends of the order of ignition of the fuses. The really poor control of the timing has an impact on the result of the blast which has to be taken seriously in account. Moreover, the blasters only rely on their experience to know whether the time to leave the blast area is sufficient compared to length of the fuse. Even if in this mine this method has not yet created problems it cannot be considered a safe practice.

6.2 **Methods: Blast design**

The design of the blasts has been performed after preliminary surveys of the site, taking into consideration the limitations of the available equipment. The main limitations imposed on the design were:

- the section of the existing tunnels: roughly 2 m wide x 2.5 m high, but with a very irregular profile;
- the diameter of the drilling bits: only 1”1/2 was available; the theoretical pull of 1.60 m is imposed by the rod’s length;
- the size of fragments: due to the size of the loading and hauling equipment fragmentation had to be taken into account, since large boulders could not be loaded or hauled;
- the impossibility of the accurate control of the blast timing.

Cut holes

Due to the reduced section of the tunnel the opening cuts have been designed with parallel holes. The only drilling diameter available made the realization of a large-diameter hole being left uncharged impossible. Hence an opening cut with four central holes drilled close together (***Figure 38***) has been designed to obtain an equivalent diameter of 88 mm. The remainder of the opening cut has been calculated with the method suggested by Oloffson (1988). Only three rounds of the opening cut have been designed, since the width of the tunnel offered no space for a fourth.

Stoping holes

The stoping holes have been distributed with an angle of breakage of around 90°, and the charge has been calculated following the method by Olofsson (1988). Considering that the column explosive is a homemade version of ANFO with a low disruptive power, a lower burden has been left for the wall holes and one as low as possible for the floor holes. The calculated charge is shown in ***Figure 38***.

Firing sequence

The firing sequence has been designed by considering that two operators ignite the fuses at the same time, each one operating on half of the face (making the coordinated contemporary ignition of two holes on opposite sides of the face possible, see ***Figure 41***), and that no more than three fuses can be jointed and ignited at the same time.

6.3 Execution and results of the drilling and blasting operations

Drilling team

The MO company provided two drilling teams, composed of a drill operator and his assistant. The operator handles the machine and drills the blastholes (***Figure 39***), while the assistant helps in the handling of the rod to position the bit, operates the admission valves of compressed air and water, and helps during the re-positioning of the grip of the pneumatic jack. The drill operator, who is more experienced, is also the blaster in charge. Team no.1 was composed of two rather young miners, who were available to perform different schemes than those ones they were used to, and who were curious to learn new techniques. Their work was accurate and precise. Team no.2 was composed of a slightly older drill operator who was very attached to the techniques he had always adopted. This resulted in a resistance to perform new techniques, and in order to follow the design constant supervision of the drilling operations was needed. The accuracy of drilling and therefore the quality of the result depended heavily on the team, which was higher when team no.1 operated.

Accuracy and result of the drilling

Some differences between the design and the realization are unavoidable in each working site. Nevertheless, in artisanal mining both human and technical factors can lead to great discrepancies that must be considered and evaluated. The main problems encountered were the following:

- depending on the team and on the willingness of the drill operator to follow the instructions of the engineer the results could vary widely from the design;
- it has been necessary to regularize the blasting pattern because the drillers find it operationally easier to visualize and hence realize a grid based on a squared and regular pattern, even in the opening cut (***Figure 38***);
- the manual drill could not reach the level of the roof holes, and therefore such holes were realized with steeper angles with respect to the horizontal plan than the designed look-out angle (***Figure 38***).

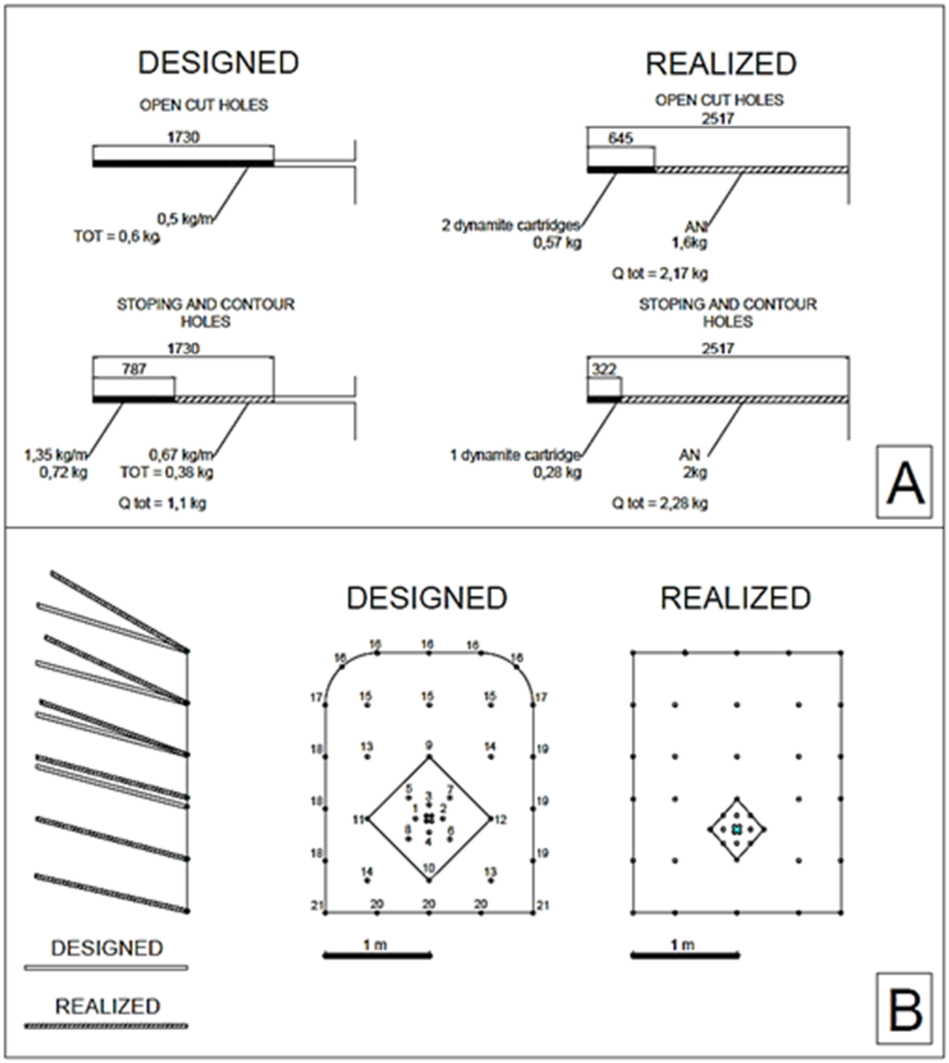

Figure 38- A-Differences between the planned and realized drilling pattern B- Differences between the planned and realized charging of the holes

Charging

In the mine the holes are traditionally charged as follows: a) opening holes: 1 dynamite primer + 1 unprimed dynamite cartridge + AN up to the collar of the blasthole; b) stoping and contour holes: 1 dynamite primer + AN till the collar of the blasthole (See figure ***Figure 38***). This method overcharges the holes. Nevertheless since psychological resistance was encountered when suggesting a different charging scheme, and considering the unknown behavior of the AN, the blasters have been left free to charge the holes in the manner in which they were accustomed. Results proved that this did not affect the results in a significant way in terms of overbreak, suggesting that the behavior of this AN explosive is in the range of a low detonating explosive or a very strong deflagrating explosive.

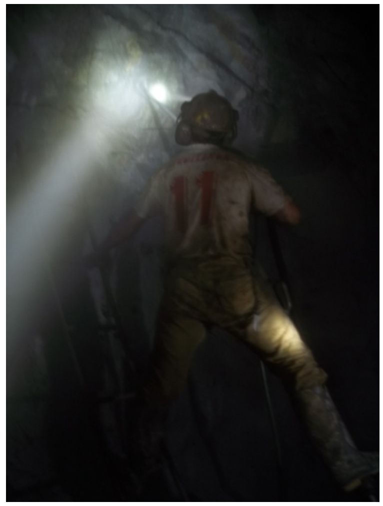

Figure 39 - Drilling

Figure 40 - Charging

Figure 41 – Ready to fire

Table 18-Differences between the designed and realized blasting pattern

Symbol	Parameter	Unit	Value	
			Designed	*Realized*
Sh	Design section height	[m]	2,5	
Sw	Design section width	[m]	2	
Ad	Design section	[m^2]	5	
	Open cut section		0,71	0,15
L_d	Pull	[m]	1,6	1,5
Mp	Pull efficiency		0,94	
V	Blasted volume	[m^3]	8	7,5
ρ rock	Rock density	[kg/m3]	2,65	
T	Tonnage of one blast	[t]	21,2	19,9
Φ	Hole diameter	["]	1,50	1,50
Φ	Hole diameter	[mm]	38,1	38,1
Q	Charge per hole	[kg]	1,1	2,1
L_Q	Charge length	[m]	1,1	1,5
N	No. of holes		44	44
Q_{TOT}	Charge per round	[kg]	48,4	93,2
P.F.	Powder factor	[kg/m^3]	6,05	12,43

Results of the blasts

A comparison between designed and achieved blast parameters is shown graphically in *Figure 42*and listed in detail in ***Table 18***. The pull efficiency is good (over 90%) despite the large dissimilarity between the designed open cut section and that realized. The dissimilarity, however, caused an increase in the burden on the production holes, and it was observed that the pull efficiency in the cut was systematically higher than in the others parts of the tunnel. In order to guarantee the regularity of the finished tunnel the cut section in the last round was shifted from the center of the section to the lower left-hand side (***Figure 42***). A broad measurement of the height and width of the tunnel after each blast showed that the section had approximately the same area as designed section, and that the overbreak was reasonably low. Some half casts were visible despite the lack of timing. Nonetheless, they were too few to allow the calculation of a half cast factor (Mancini and Cardu, 2001). ***Figure 42*** shows the position of some visible blastholes following the last round of regularization. The difference from the planned position is due to the low precision in the positioning of the rod and in setting its inclination. Regarding fragmentation, the only constraint was the size of the pneumatic loader which could not charge fragments larger than 50 cm. The result was very positive as no secondary breaking was required and hauling was rapid and efficient.

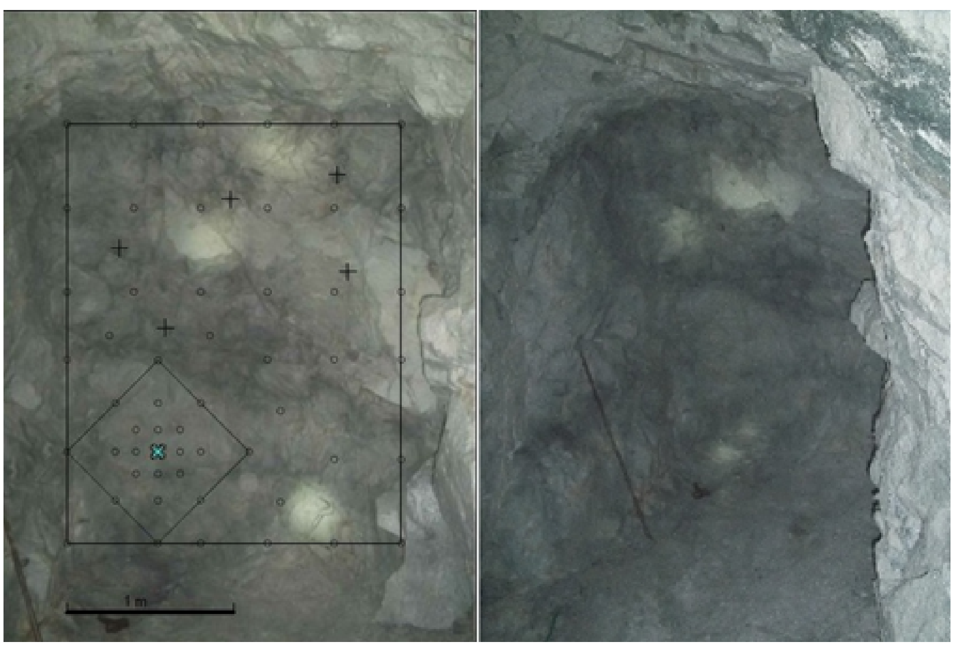

Figure 42 – Final result of the blasted tunnel. In the left picture the blast design is overlaid on the picture of the final tunnel. The impression of over-break is due to perspective, and the profile is better seen in the image on the right. In b/w for a better contrast of the pictures taken underground

6.4 Other blasting operations

Scaling

The presence of a set of discontinuities creating an unstable wedge made scaling operation necessary. One hole was drilled in the roof and the wedge was been blasted with only one cartridge of dynamite. The blasting of the wedge was the subject of debate with the drillers who, due to their lack of geotechnical knowledge, did not perceive the danger. The result of the blast was the detachment of not only the visible wedge but of about 1/3 m^3 of unstable rock which fell in the tunnel. The result of this operation had a very strong psychological effect on the workers, and broke their initial resistance to the leading role of the outsourcing engineer.

Blasting the concrete frame

The massive concrete frame, built by SADCO, was located at the entrance of the adit to support the metallic door that originally sealed the tunnel. The frame was composed of 1.50 m thick concrete. The presence and position of steel reinforcement bars was unknown. According to Olofsson (1988) the specific charge for blasting concrete varies greatly with the quality of the concrete, but overall with the amount of steel reinforcement. This author suggests distributing the explosive in as many holes as possible because commercial explosives do not cut steel bars but instead fragment the concrete around them. After a preliminary survey of the door, it appeared that in a previous similar blasting operation a firing pattern with spacing of about 0.2 m had given a good result; as a result a similar pattern was adopted. The result of the blast was clean and accurate, the frame was been totally eliminated and the fragmentation of the concrete was homogeneous (***Figure 43***). The steel reinforcement mainly consisted of old drilling rod and recycled bars that were later cut by mechanical means.

Figure 43 - Preparation and result of the demolition blast of the concrete wall. In b/w for a better resolution of the pictures taken underground. In b/w for a better resolution of the pictures taken underground

Stoping along the adit

The widening of over 25 adit sections has been performed in order to allow the passage of the borehole drilling machine. The undersized sections were individuated by a simple effective method: a wooden frame with the same overall shape of the borehole drilling machine was pulled through the adit, and the sections in which it got stuck were identified with paint spray. For the widening, stoping blastholes diverging from the axis of the tunnel have been drilled. The holes were loosely charged according to the varying burden. The results of these blasts were very poor in terms of contour, but achieved the goal of widening the section of the tunnel and producing good fragmentation to allow for rapid and effective hauling.

6.5 **Discussion**

The execution of this work provided precious lessons about the main problems that can be encountered in analogous situations of artisanal underground operations. In ***Table 19*** the main criticalities identified during the work are detailed, along with their possible consequences and some preliminary guidelines for their solution.

Table 19- Criticalities and suggested improvement

Criticality	Consequences	Improvement
Use of outdated equipment	• High vibration level • High noise level • Mechanical hazard • Presence of dust • Low productivity	• Replacement of the equipment with a modern one (out of the reach for many small-scale mining companies) • Generalize the use of personal protective equipment, • Formation and training of the operators
Use of handcrafted explosive	• Explosive hazard • Possible formation of poisonous gas.	Both the workers and the mine management must me formed on explosives functioning and characteristics. This will allow them to make responsible choices.
Pyrotechnic initiation of the blast	• Explosive hazard • Impossible timing of the blast.	Shock tube initiation (Timing control can improve the blast performance, decreasing explosive consumption and specific drilling). Shocktubes are already in use in nearby artisanal mines.
Unsafe explosive handling and transport	• Poor blast efficiency • Explosive hazard	Formation and training of the operators on the principles of blast design and safe explosive handling
Absence of ventilation	• Risk of intoxication • Production slowed by the long ventilation shifts	• Short term solution: compressed air as a pressing ventilation system (it offers little reliability because it is impossible to calculate the amount of exhausted air still present at the end of the shift, and the rate of air renewal in the mine). • Long term solution: up to date ventilation system (the investment can be out of the reach for many small-scale mining companies)
Distrust toward the engineer	• Reticence to follows instructions • Low productivity • Health and safety hazard	In future works, it must be shown as soon as possible a case of clear success of engineering knowledge (the solutions and improvements proposed by the engineer should be effective since the first attempt, because any "failure" will be eternally remembered by the miners, supporting their argument that "engineers don't know": Hentschel *et al.*, 2002).
Lack of geotechnical knowledge	• Hazard of collapses and rock falls	Formation and training of the operators on the hazards of rock fall in underground environment (rock falling is one of the main causes of accidents in small-scale mining: Hentschel *et al.*, 2002).

6.6 Suggesting a formula for safe pyrotechnic ignition

When the only available ignition system of the blast is pyrotechnic, a quick safety improvement can be obtained by implementing the following formula. Considering a hole-to-hole ignition interval dependent on manual operations and a nominal tolerance of the safety fuse of ±10%, the safety of the ignition is guaranteed if the condition of the following formula is satisfied.

$$n_{gf} \times 5 + t_{ra} < L_f \times c_r \qquad (25)$$

Where n_{gf} [-] is the number of groups of fuses that compose the blast (a group of fuses is composed by all fuses that are lit together), 5 [s] is the average time necessary to initiate one group of fuses with a lantern, L_f [m] is the length of one fuse, c_r [s] is the average combustion rate of the safety fuse, t_{ra} [s] is the time needed to reach a safe place before the blast. It must be noted that:

- the combustion rate of the safety fuse, and its accuracy, greatly depends on the manufacturer and operational conditions, and should always verified on field under the real operating conditions;
- one group of fuses must only comprise of fuses that are lit at the same time.

The most critical point is the calculation is t_{ra} . The time needed to reach a safe place can be calculated as $t_{ra} = d_s / s_w$, where d_s is the acceptable safety distance, and s_w the average walking speed of the operators. In the case of underground blasts, in order to establish a safe distance the factors that must be taken into account are: level of blast noise, ventilation, roof characteristics and the roof control plan of the mine. The limits of the blast area need to be adjusted accordingly. Under the conditions described, the authors considered a safe distance not less than 400 m to be acceptable. For traffic engineering design purposes, Knoblauch *et al.* (1996) suggested adopting a speed of 0.91 m/s for old pedestrians and 1.22 m/s for younger pedestrians. Considering the difficult walking conditions underground, it is recommended using the conservative value of 0.91 m/s.

6.7 Final remarks

All the criticalities identified during this work can be divided into three main groups:

- use of unsuitable and unsafe supplies and equipment;
- Lack of technical knowledge;
- “Human factor”.

The consequences of these criticalities can be classified in the following two categories:

- productivity limitation and
- OHS problems.

It can be observed that these three categories of criticality match the characteristics commonly attributed in the literature to artisanal mining: low productivity, intense labor activity, low technological knowledge, low degree of mechanization and low levels of health and safety awareness (Hentschel *et al.*, 2002, Seccatore *et al.*, 2012). The only characteristic of artisanal small-scale mining not present in this case is informality, thanks to the presence of the juridical framework dedicated to small-scale mining in Ecuador. During the work some short-term solutions have been implemented, but in order to obtain significant improvements it is evident that long-lasting solutions are needed. This is true with regard to health and safety issues, because effective solutions should be based on a risk management plan that is implemented from the design phase of the mining project (NIOSH, n.d.; OHS, 2011) but it is also true with regards to efficiency and productivity issues. In order to be effective, an eventual modification of the working method must be carried out with an integrated approach, both modernizing the equipment and training the workers and not with simple punctual corrections. A long-term solution requires large initial investment and a long time for implementation. For these reasons long-term solutions are commonly out of the reach of artisanal mining companies. Chapter 5 of this theses addressed the initial stage of the implantation of long-term solutions for the shift of this artisanal mine towards a responsible small-scale operation.

6.8 Acknowledgments

Many thanks to Lorenzo Magny, with whom this chapter has been drafted.

7 OVERALL CONCLUSIONS

Gold is the main commodity exploited by AM. Between 380 and 450 t of gold are produced annually by about 16 million artisanal miners in the world. These numbers refer to gold only. AM of other commodities lays beyond estimation: the total population of artisanal miners and the amount of minerals produced can only be higher.

Not all SSM is artisanal, and this is a most important aspect that must be highlighted. The correct definitions are:

- Small-Scale Mining (SSM): a mining activity defined by low productivity (few hundreds of t/d ROM), low capital expenditure and revenues.
- Artisanal and Small-scale Mining (AM): a subset of SSM, falling in the same range of productivity and investment, but that possesses as well the characteristics of rudimentary mechanization, inefficient recovery, unsafe working conditions and labor exploitation.

To understand the aspects that characterize AM, indicators must be used to give a quantitative and not qualitative definition. Along this thesis basic indicators have been individuated specifically to measure the peculiar characteristics of artisanal mines (only for underground units at first), which differentiate the latter from industrial mines. The purpose of these indicators is the standardization of artisanal mine evaluation on a quantitative basis, an important yet currently unavailable research tool. The indicators collected during field visits are intended to contribute to the establishment of standardized artisanal mining databases, thus creating the possibility for subsequent statistical analysis, and more importantly, quantitative evaluation of improvement measures taken over the years.

The most important thing is that the analysis of such indicators enables the potential sustainability of an underground artisanal mine to be measured, as well as its upgrade over time towards classification as an industrial small-scale mining unit.

Such an upgrade must be an innovation towards efficiency: it has been demonstrated that the path for sustainability goes through efficiency.

Efficiency has costs: the cost to innovate the operation towards effective methods using adequate technology and optimized equipment. This cost must be covered by an investment, and when the cost is high (for a high leap in innovation), it is most likely to come from outside of the small-scale mining enterprise: external investment

To achieve favorable conditions for investment, in this Thesis has been proposed a new approach for the management of mineral resources and reserves specifically for small-scale mining. The proposed approach to calculate this reserve contains two main concepts: a “minimum reserve” required for the project start-up and “replication” to confirm the feasibility of continued operation. The minimum reserve to be proved can be calculated considering the expense items contained in the CAPEX and OPEX of the mining business, together with the cost of geological exploration.

The proposed methodology, applied to an actual underground gold mining operation, proved that the reserves required for that particular small-scale operation are in the order of magnitude of 1/1000 of that required for large-scale mining, when both businesses possess the same level of feasibility.

A responsible and sustainable form of SSM is possible, achievable and viable. If properly dealt with, SSM can be turned into an industrial operation that can help the economical development of the area where it operates, and create positive externalities such as education, capacity building, culture of efficiency and environmental awareness.

Paraphrasing the famous expression coined by Fritz Schumacker, small mining can be beautiful.

8 DELIVERABLES

Paper published in peer-reviewed journals

- SECCATORE, J. ; VEIGA, M. ; ORIGLIASSO, C. ; MARIN, T.; DE TOMI, G. (2014) *An estimation of the artisanal small-scale production of gold in the world*. Science of the Total Environment , online, in press
- SECCATORE, J.; TATIANE M. ; VEIGA, M. ; DE TOMI, G. (2013*) A practical approach for the management of resources and reserves in Small-Scale Mining*. Journal of Cleaner Production , online, in press.

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- SECCATORE, J. ; DE TOMI, G. ; VEIGA, M. . *Efficiency as a road to sustainability in Small Scale Mining.* Materials Science Forum , 2014.
- DOMPIERI, M.; SECCATORE, J. ; DE TOMI, G. ; NADER, B. *An innovative approach to mine blast fragmentation management using complexity analysis: three case studies.* Materials Science Forum , 2014.

Papers submitted to peer-reviewed journals

- SECCATORE, J. ; MAGNY, L. ; DE TOMI, G. *Technical and operational aspects of tunnel rounds in artisanal underground mining.* REM – Revista Escola de Minas
- VEIGA, M. ; ANGELOCI-SANTOS, G. ; NIQUEN, W. ; SECCATORE, J. *Training Artisanal Gold Miners from Piura, Peru.* Journal of Cleaner Production.

Book Chapters

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- WADE, L. (2013) *Gold's Dark Side*. SCIENCE n. 27 September 2013: Vol. 341 no. 6153 pp. 1448-1449

Volume of peer-reviewed journal (as organizer)

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- SECCATORE, J., (2012) *Technical Report of the inspection of an underground gold mine in Piura – Peru*. Report prepared for the University of British Columbia on behalf of the US Department of State

List of indicators

- List and field record forms of Basic indicators for the characterization of underground artisanal mines.

9 START-UP OF PILOT PROJECTS

The work for Sustainable SSM performed during this thesis produced the start-up of two pilot projects on real scale that address the sustainable management of small-scale mines. Who writes funded the two projects and acts as their coordinator.

- **Experimental Mine Project, Brazil – Open-Pit**
  The Sociedade Extrativa Dolomia LTDA, was founded in 1935 in Taubaté- SP, at that time with manual extraction of limestone, producing about 400 t/y of limestone. Only recently the mine came out of legal characterization of SSM according to the Brazilian mining law(the threshold is 100 000 t/y, and currently the production is 380 000 t/y). The mine for more than ten years has been working with the researchers of the current NAP.Mineração in field research and training of students. Thanks to these initiatives, the Dolomia mine became an example of a Sustainable Mining . To formalize the partnership, who writes promoted the signature of a scientific agreement between NAP.Mineração and Dolomia, ("Contrato de Cônvenio Soc. Ex. Dolomia LTDa. – USP – 11/11/2013") . The Dolomia is now the Experimental Mine of NAP.Mineração, and who writes has been appointed as **Project Coordinator**. The scope of the Experimental Mine Project is to research on real scale adjustments and calibration of equipment, methods and procedures for small-scale mining without compromising the current operation.

- **Zaruma Project, Ecuador – Underground**
  The mine is the one described in Chapters 5 and 6 of this thesis. At the moment the mine passed the stage of the geological exploration (***Figure 33***, whose preparation is described in Chapter 6) is at the stage of the Engineering project ("proving the reserve" as in ***Figure 33***). Who writes has been appointed **Project Manager**. As soon as mine opening (***Figure 33***) will begin, a similar agreement will be signed to appoint the Zaruma project as "Underground experimental mine", where will be improved and calibrated the equipment, methods and procedures to transform an underground AM into a sustainable SSM.

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