DELIVERABLE 2.1

REPORT ON THE DELPHI SURVEY

Defining FET research topics supporting the ICT challenges of mineral extraction under extreme geo-environmental conditions

Project Number FP7 - 1 318149

Acknowledgement

The EXTRACT-IT Partnership wishes to express its sincere gratitude towards all experts, who participated in the Survey.

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1. Introduction

EXTRACT-IT aims to identify emerging and potentially disruptive trends in how Information and Communication Technologies (ICT) is used in future ultra-deep mines. These trends may not conform to current mainstream research in mining/ICT but they could have the potential to turn into novel applications in the mines of the future (timeframe 2050), where the ambient conditions represent some rather complex challenges for ICT. The challenge for EXTRACT-IT is to identify such potential future applications and develop topics for Calls for Proposals under the Future and Emerging Technologies (FET) Programme in Horizon 2020[1] EU Framework Programme for Research and Innovation that could support the development of these future trends in the present. Given the long timeframe and the great deal of uncertainty of such future developments the Delphi technique was seen as an important element in the 1-year EXTRACT-IT investigation.

A Delphi survey is a structured group communication/interaction process that can be used to investigate issues on which unsure and/or insufficient knowledge is available. Although there are no accepted standards as to how Delphis are conducted, the following key features are generally considered a basis for the Delphi technique:

- Facilitates group interaction whilst the anonymity of the experts is maintained
- Carried out in multiple rounds
- The questionnaire used in the subsequent round is based on the evaluation of the previous round
- Results of each round are presented to the experts
- Experts may revise their earlier answers in light of the replies by other experts
- The questionnaire is designed in a way that feedbacks on the issues at stake are always collected

Since Delphi surveys involve making judgments about uncertain future developments, the experts involved in the study only give estimates based on their professional experience. The evaluation of Delphi surveys can be qualitative, quantitative or a combination of both.

In EXTRACT-IT the objective of the Delphi (similar to the project as a whole) was to create a platform for discussions and „generate" comments and ideas, which in turn could be used for the appraisal of ideas for future Calls. Accordingly the "qualitative dimension" i.e. the ability to collect expert opinions in forms of comments and ideas was considered much more important than the quantitative dimension of the study, i.e. the statistical expression of the different levels of consensus reached against particular future issues. The goal of the EXTRACT-IT Delphi study was thus to „poll" the greater scientific community and collect structured opinions from those, who could not participate in the workshops or could not express their opinions otherwise.

The EXTRACT-IT Delphi survey had the following key phases:

1. Creating the Statements
2. Creating the Survey Platform
3. Running the Survey
4. Evaluating the Survey

[1] http://ec.europa.eu/research/horizon2020

The above process was iterative i.e. the implementation of Round 1 was followed by an evaluation of expert input and the design of new set of questions and pre-conditions, after which the Survey was run again. The EXTRACT-IT Delphi was designed as a 2-round survey only.

2. The Definition of the Delphi Statements

2.1 Initial Delphi Statements

For the creation of the Statements for the Delphi survey a combination of an internal Mind-mapping exercise and the outcomes of two Foresight Workshops were used. The Leoben Workshop (6-7 February 2013) created the basis for the First Round of the Delphi, whereas the workshop in Brussels (12-13 June 2013) was used for the evaluation of Round 1 and the elaboration of Round 2 Statements and pre-conditions.

In the initial Mind-mapping activities only consortium members were involved, with the goal to define an initial pool of concepts that could be discussed during the Appraisal workshop in Leoben, Austria. The objective of this first workshop was to discuss technological challenges but also to define the scope, issues and strategies for the Delphi survey that were expected to mobilise experts from all over the World. In order to facilitate discussions three different Future World Scenarios were created to serve as a basis for discussions. This was seen as important, so that less efforts are diverted into reaching an agreement as to how the future looks like and there could be more focus on how mining and ICT will have evolved against the backdrop of these scenarios.

Note: More details on the Workshop Methodology is provided in D2.3 Report on the Foresight Exercise

The initial Delphi Statements were developed in the following three “Future World” Scenarios:

Scenario 1. European Renaissance
“The strong political union combined with substantial funds invested into R&D at the right time has resulted in a strong momentum for Europe to pass through the global economic recession and since the mid 2020s Europe has become a leading global power based on an all-inclusive “knowledge economy” under the supervision of a strong European Research Council, and a whole set of other new European institutions designed to promote innovation and European technologies.”

Suggestions by Working group 1 for Delphi statements:

- ICT in deep mining will make the EU self sufficient in mineral resources.
- Multifunctional robots can do mining and underground processing
- Fully automated mining is a reality.
- Robot-controlled bio-mining is the leading production method in unpredictable ore bodies
- Self-repairing and self-replicating robots reduce downtime
- ICT, geology and mining are integrated in one department at all mining universities in the EU
- Safe and attractive workplaces are a prerequisite to recruiting young people to the mining sector.

Scenario 2. Business as usual
“In this scenario the EU is still the economic and political association of independent, autonomous member states that it was in the 2010s. The EU continues to operate through a system of supranational independent institutions and intergovernmental negotiated decisions taken by the member states. Due to the way decisions are taken, the EU often is not able to speak with one voice on the international tribune. The continent still has no coherent foreign policy and lacks an efficient

military capacity. Due to its weak position in global governance, Europe finds it difficult to compete for global resources."

Suggestions by Working group 2 for Delphi statements:

- Collaborative robots will selectively mine ore deposits
- Mining robots will have on-site access to different tools and sensors to allow them to explore, extract, process and transport the ore, waste and reagents
- All power used in mines deeper than 1000 m will be generated from on-site geothermal energy
- The European Mining Agency will reform Europe's mining laws and regulations and will coordinate R&D and educational policy for mining
- Access to deep mines is through drill holes rather than shafts
- Self-assembling robots are used for tasks which require larger equipment
- Robots will manage the waste to avoid any environmental impact
- Deposit discovery is done by combination of geological intuition and predictive models
- Ground proofing of exploration models is done by (tele-operated) exploration robots
- Mining ICT is interoperable with global ICT standards
- Plug-and-play solutions eliminate the need for ICT experts working for mining companies
- All underground communication is wireless
- Robots have devices for absolute georeferencing
- Zero impact mine is reality

Scenario 3. Fragmented Europe

"In Europe there is very limited public finance available and this alone is not sufficient to meet infrastructure needs, which are huge and growing. In the aftermath of the series of financial crisis and bearing the burden of indebtedness of previous decades, most EU countries are restricted in their capability to invest and to mobilize resources for long overdue development and improvements of existing infrastructures, which would be important for the well-being of citizens. Quality services, are, however available at a premium price, through private corporations that increasingly take over the provision of critical infrastructure (security, health-care, ICT, etc)."

Suggestions by Working group 3 for Delphi statements:

- Artificial-intelligence (AI) supported permitting procedures significantly reduce the time needed for getting permission to open a new mine and will reduce the effect of conflict of interest and corruption
- Underground mines are fully controlled by AI
- Although underground mines are fully controlled by AI there are still people working in mines underground
- Dangerous and heavy tasks are no longer performed by humans
- The number of people working in mines has decreased dramatically
- Plant and process monitoring is highly visualized by augmented reality
- Mining is done by small autonomous robots without creating large cavities
- Military and mining use of robotics co-evolve
- Communications between operating units are secured (uninterruptable and encrypted) and realtime
- Mining is performed as a combination of human labour, robotics and biotechnology
- Mines are fully dependent on high-bandwidth ICT infrastructure

Additional Key ICT requirements

Plenary discussions highlighted several key ICT requirements, which are summarised below

- Reduce size of equipments and sensors with increased efficiency, lower noise to signal ratio, more robust and less energy consuming
- Better real time and intelligent fusion of different sensors, multitasking standard protocol with high speed and high band width data processing in adverse conditions of high EMI and radiation
- Need for secured communication network
- Need for standardisation
- Need for cost reduction in robots (through volume and standardization)
- Devices to store energy efficiently
- Solutions for absolute georeferencing under the ground

The outcome of the Leoben workshop was a tentative list of expected ICT requirements and several initial proposals for Delphi Statements. These Statements needed further elaboration, and this work started at the subsequent project meeting in Puntagorda, Spain 25-26 February 2013.

2.2 The Elaboration of Delphi Statements

The outcomes of the First Workshop in Leoben were carefully analysed during a project workshop in Puntagorda, Spain. During this workshop it was realised that two Scenarios (European Renaissance and Business as Usual) yielded relatively similar results and gave similar impressions during discussions, whereas Fragmented Europe was substantially different. It was therefore agreed, that for the Delphi survey only two scenarios would be kept, offering two different future contexts for the participants. This allowed for the simplification of the survey structure, but still offered the possibility for the experts to choose between two future worlds. Accordingly, the European Renaissance and Business as Usual Scenarios were united into a "Prosperous Europe" Scenario. Both the Prosperous Europe and Fragmented Europe Scenarios were then elaborated using remarks and comments by the participants during the Leoben workshop. Criteria for the elaboration and definition of the Delphi statements were:

- Clarity of the statements
- Likely capacity to generate comments and discussions
- Cross-cutting through several relevant areas identified in Leoben
- Limited number, maximum 10 but preferably less

Once the Future scenarios were elaborated project partners screened through the proposals for Delphi statements by the Leoben Workshop participants, and refined them further in order to meet the above criteria. The objective of this exercise was to keep as much as possible of the original statements (and their original meanings, intentions) but also structure them in a way that all important aspects are covered with a good overlap between the two Future world scenarios. The resulting statements were the following:

Fragmented Europe "Future"

1. Dangerous and heavy tasks are no longer performed by humans underground
2. Virtual support staff in augmented reality is available in deep mines
3. In suitable formations mining is done by small autonomous robots without creating large cavities
4. Autonomous, ICT-controlled bio-mining is a leading production method
5. Collaborative robots in-situ process ore deposits

6. Deep mines can be controlled and operated from anywhere
7. Military and mining research on robotics is performed in the same research centres
8. Disabled people, senior citizens and teenagers are routinely employed by mining companies (via novel tele-working solutions)

Prosperous Europe "Future"

1. Dangerous and heavy tasks are no longer performed by humans underground
2. Virtual support staff in augmented reality is available in deep mines
3. In suitable formations mining is done by small autonomous robots without creating large cavities
4. Autonomous, ICT-controlled bio-mining is a leading production method
5. Collaborative robots in-situ process ore deposits
6. Deep mines can be controlled and operated from anywhere
7. Self-repairing robots reduce downtime
8. Deep mines are self-contained ecosystems operated by autonomous, self-replicating robots

The above statements cut through all important ICT topics that were discussed in Leoben and they were expected to generate interest and comments as well. Some Statements address specific technologies (e.g. Statement 2) others are cross-cutting, designed to generate comments across a wealth of ICT-relevant areas (e.g. Statement 1). Out of the 8 Statements in each group 2 were different and specific to the particular future (the more wealthy and stable Prosperous Europe where substantial EU-funds are available for applied/basic research vs. the grimmer Fragmented Europe where external threat is more imminent and there are limited EU-coordination of research and regulations).

Once the Statements were elaborated and agreed upon the contexts against which the Statements would be evaluated were also defined. Although the experts invited to participate in the survey would not be informed about this the contexts would be later used to rule out topics/issues that are either too hypothetical or already considered by applied research programmes:

- Likely realisation date – need to filter out developments that would occur outside the project's scope
- Required research (qualitative assessment of the type of research required)
- Technological challenges (seeking ambitious objectives)
- Future impact (understanding the likely societal dimension)

Once the content of the Survey was finalised the programming of the survey platform could be started.

3. Programming the Delphi Survey

The structure was designed in a way that in addition to the content and clarity of Statements the following requirements were also met:

- Fill in less than 15 minutes. This was seen as an important criterion. Many Delphis fail to yield decent results, because they are too long and the experts are reluctant to invest substantial time into something that is unpaid and therefore need to be done on a voluntary basis in their free time.

- Stop and continue the survey in an easy manner (no passwords). This is related to the previous point. The easier the access and implementation the more likely that the experts would in fact complete the survey.
- Preserving the Anonymity of participants. Crucial in Delphi so that the usual issues with “group dynamics” could be avoided. It was, however decided to ask the participants if their names could be noted as an “expert contributing to the survey”.
- Collecting relevant information on the participants’ background. This was seen as important, so that during the evaluation of comments the background of the experts could be correlated with the comments.
- Ability to have overall comments at the end of the survey, so that issues that were not explicitly covered – but considered important to the expert – could also be recorded. This was an important goal for the project as a whole (collecting as much comments as possible) but also for the preparation of Round 2.
- Stable platform is used, computer problems are alleviated. Given the fact that the experts would be contributing in their free time the survey must be designed in a way that it would run properly on all browsers.

In order to satisfy the above it was decided to develop the survey code from scratch (instead of using Surveymonkey or a similar solution). This required some additional work and some minor delays as well in implementation, but the final quality and flexibility compensated for this.

Below is an overall structure of the Survey. The actual version (Screenshots) is Annexed to this report.

Welcome to the Extract-It Delphi Survey!

Extract-it is a 12-month project supported by the European Commission's 7th Framework Programme. Our objective is to identify exploratory ICT research topics supporting the future needs of the extractive industry.

Completing the survey will take about 15 minutes (8 questions). As an expert participating in the survey you will have access to the results, including comments and ideas made by the other experts.

Statements for the survey were formulated with the help of a foresight-workshop organised in Leoben, Austria, 6-7 February, 2012.

Please select your Future

Prosperous Europe	**Fragmented Europe**

Kindly note that only one future can be selected. Once selection has been made your choice is final.

Before selecting your future please read the short summary:

Prosperous Europe (link to pdf)
Fragmented Europe (link to pdf)

I have read the above summaries and My Future is:

Prosperous Europe ()
Fragmented Europe ()

Proceed

Thank you for your choice! Your Future is: (name of Future here). You are kindly asked to formulate your responses in a way that they consider the general trends as outlined in the Future summaries.

The Survey is Anonymous (your name will not be disclosed along with your replies). The following data is for our internal processing.

Title

First Name

Surname

Nationality (select from list)

Gender (Male/Female)

Age

Sector:

Academy () **Industry ()** **Public/Government ()** **Other:….. (specify)**

How would you characterise your professional background? Please indicate your level of expertise in the following areas.

Raw materials (general)	Non-expert 1() 2() 3() 4() 5() 6() 7() 8() 9() 10() Specialised expert
Mining engineering	Non-expert 1() 2() 3() 4() 5() 6() 7() 8() 9() 10() Specialised expert
Earth sciences	Non-expert 1() 2() 3() 4() 5() 6() 7() 8() 9() 10() Specialised expert
Mining and ICT	Non-expert 1() 2() 3() 4() 5() 6() 7() 8() 9() 10() Specialised expert
ICT (general)	Non-expert 1() 2() 3() 4() 5() 6() 7() 8() 9() 10() Specialised expert
Other (specify)	Non-expert 1() 2() 3() 4() 5() 6() 7() 8() 9() 10() Specialised expert

Proceed to the Questionnaire

(You can interrupt your survey anytime and return to continue by clicking at the link given in the invitation email).

Survey will close on: (date written here)

Number of days left to complete the survey: (number of days till closure)

Proceed

Statement 1 of 8 / (Name of Future here)

"STATEMENT 1"

Please indicate by which date the above statement could be realised.

Today () 2030 () 2040 () 2050 or beyond () Never ()

The achievement of these statements requires today:

Substantial basic research ()

Substantial applied research and some basic research ()

Applied research ()

The corresponding present day technological challenges are

low () moderate () high () very high ()

The impact on our future society is

low () moderate () high () very high ()

Please explain your choices, and list any particular research challenges, technological requirements, pre-conditions*

*** A brief explanation of your choices is kindly requested for all Statements (in relation to the particular Statement). At the end of the survey you will have the chance to give overall comments as well.**

Next

When you click „Next" your answers are automatically saved. You can interrupt the survey anytime and return later to continue.

Statement 2 of 8 / Name of Future

STATEMENT 2…(8) WRITTEN HERE

Please indicate by which date the above statement could be realised.

Today () 2030 () 2040 () 2050 or beyond () Never ()

The achievement of these statements requires <u>today</u>:

Substantial basic research ()

Substantial applied research and some basic research ()

Applied research ()

The corresponding present day technological challenges are

low () moderate () high () very high ()

The impact on our future society is

low () moderate () high () very high ()

Please explain your choices, and list any particular research challenges, technological requirements, pre-conditions*

*** A brief explanation of your choices is kindly requested for all Statements (in relation to the particular Statement). At the end of the survey you will have the chance to give overall comments as well.**

Back **Next**

When you click „Next" your answers are automatically saved. You can interrupt the survey anytime and return later to continue.

Last page only:

What other modalities of ICT you feel would be important in future deep mines. List keywords and elaborate if possible. You may also formulate a "Statement" similar to the ones you have just evaluated.

Can we list your name in our final report as an expert contributing to the Delphi survey?
Yes ()/ No ()

Submit Now - Please note that once you have submitted the survey you will not be able to edit it any further.

Submit Later - Your form will be saved. You can return anytime for further editing. The form will be automatically submitted on /Date/ Brussels time.

After submission:

Thank you very much for your time. We will contact you again when the results are aggregated and evaluated.

4. Implementing the Delphi survey

Given the very short project timeframe the EXTRACT-IT Delphi was planned for two rounds only. Although this did not facilitate reaching a strong consensus on the issues, it did allow substantial commenting and in particular sharing ideas and visions among the experts.

It was decided that personalised "Tokens" are to be sent out with the contact e-mail, so that the often tedious login/password system could be eliminated and the typical problems associated with it (e.g. forgotten password) could be avoided as well. Instead the Tokens identified the users and it was possible for them to interrupt and continue the survey anytime by clicking on the personalised access link they received via email.

4.1 Round 1 Results

The Survey was launched on the 25 April with a Deadline on 15 May. The deadline was prolonged two times so that a higher number of responses could be to obtained. The first extension was 21 May, followed by a second one of 28 May.

Prospective experts were identified based on their participation in related expert workshops, studies and European projects. Representatives of the European Innovation Partnership on Raw Materials (EIP) were also invited. Out of the 300 invited experts eventually 74 participated representing 29 Countries World-wide. The survey was anonymous but the following experts wished to be mentioned as an "Expert contributing to the survey":

1. Prof Nicholas Arndt
2. Dr Ing José-Luis Fuentes-Cantillana
3. Dr Stephen Henley
4. Dr. Jakub Jirásek
5. Prof Balz Kamber
6. Mr Zeljko Crnojevic
7. Mr Vitor Correia
8. Dr. Gorazd Žibret
9. Dr Declan Vogt
10. Dr. Imre Gombkötõ
11. Prof. Claudio Rossi
12. Dr Neill Wood
13. Dr Delia Evelina Bruno
14. Dr Dmitry Ruban
15. Prof. Zach Agioutantis
16. Dr. Zoltán Horváth
17. Dr. Emilio Nieto Gallego
18. Prof Jens Gutzmer
19. Dr Markku Iljina
20. Mr Juha Kaija
21. Prof. Kari T. Koskinen
22. Dr. Kris Piessens
23. Prof Yang Gao
24. Prof Oliver Langefeld
25. Dr. Horst Hejny
26. Prof. Jan Johansson
27. Dr. Tapan Majumder
28. Dr Justine Lacey

29. Dipl. Ing. Felix Gaul
30. Dipl.-Ing. Jan Berg
31. Prof Leslie Gertsch
32. Prof Amin Hammad
33. Dr. Debdas Ray

41 experts wished to remain anonymous.

Representative comments for each of the statements are provided on the following pages, the full database dump is Annexed to this report.

Prosperous Europe

„Dangerous and heavy tasks are no longer performed by humans underground"

- …The key element is to forget about individual equipment and look at how to automate entire mines or mining systems. It is as much about automating the flows of information between parts of the mining process (i.e. drilling to grade plans, surveys to truck routes) as it is about automating machines. In fact, automating a particular machine is easy, and the technology is already here. The challenge is getting that machine the right information in real time.
- Machine and moving component operation in high moisture, dust and temperature should be stable (advanced materials and technical solutions, self-curing moving parts) and monitored. The unexpected machine failures, wear and spare part replacements underground, the services and analyses underground (robots and moving analyzators).
- Wireless communications through the rock - and absolute geo-referencing underground. In situ ore processing. Efficient geothermal (or other) energy generation underground
- Sensors for appropriate monitoring, automation in rough environment, adaptation of actuation systems for underground application, different conditions in almost every operation, legal framework
- Development of guidelines for early and critical stages of mine design… detailed visions of different levels of automation underground. • A systematic review and quantification of the health and safety advantages and disadvantages of different levels of automation.
- Robots: Exo-skeleton to make the miners much stronger and less tiring. Energy: Improvement in energy supply is needed to let them work day and night. Wireless communication (3D GPS) through 4000 m of rocks: not yet available
- Development of multi tasking robots with sensor fusion VV Large scale integration of memory chips and processor that can function under high EMI and radiation levels.
- Such technology already exists in special cases like the Kiruna iron ore mine in Sweden. We need significant reductions in investment costs to make this technology the standard technology in underground mining
- Energy efficiency of autonomous devices have to be increased significantly, autonomy of robotic devices has to be increased
- Reliable sensing systems and smart decision systems need to be developed for autonomous mining. With these pre-conditions met, future smart mining machines that explicitly use these technologies can be developed. This might lead to autonomous mining machines that may highly reduce the amount of man hours needed to perform dangerous tasks underground.
- Most of the dangerous and heavy tasks in non-artisanal mining are performed by machines today, but humans are still in the very near vicinity for many of them. I believe this will reach the goal stated above by about 2020-2025. The impact will be low because I am taking the present state of affairs, in which this has been nearly achieved, as the baseline.

Realisation date		**Research requirement**	**Tech. challenges**		**Future impact**	
Today	9%	Applied research 17%	low	0%	low	4%
2030	40%	App and some basic 79%	mod	23%	moderate	15%
2040	26%	Subst basic res 4%	high	56%	high	51%
2050/	21%		v high	21%	very high	30%
Never	4%					

Prosperous Europe

„Virtual support staff in augmented reality is available in deep mines"

- This development will result in entering more dangerous rock regimes, thus security will gain additional importance, in particular with regard to the reliability of "back-up connections" for emergencies
- Real time 3D spatial maps, real time location of personnel equipment
- Use of the technology based on IBR (Image-Based Rendering) to produce virtual environment. Compared with the computer graphics method, it does not need the special hardware support or the complex 3D modelling, and moreover it can simulate the scene with high fidelity and reappear the real world very well. Technical complex machines require frequently expert knowledge and sometimes also the direct support by the manufacturer. Interactive 3D for support of underground repairs in the mining industry is a challenge to deal with.
- To be honest, not sure what "virtual support staff" is supposed to mean?
- Broad Band Wireless communications underground, 3D visualization ergonomic tools
- Fusion of 3D vision/graphic simulation with suitable s/w for robotic control.
- Again, I would be highlighting the level of acceptance of these new forms of technology in the workplace. What are the perceptions of risk and safety? How are staff trained to work in these new virtual environments? While we may recognise virtual support staff in our daily lives (iPhones and GPS units), this industrial application may require a paradigm shift among the workforce (and their management).
- For me this a matter of software development. I do not see this as a big problem. If the support staff is not virtual but for example robotors which are able to do repair work underground I see a bigger task ahead to develop such devices. But the example of repairs in deep water off-shore development shows it can be done-- only in mines it has to be done less expensive.
- Developing countries, with abundant cheap, but relatively unskilled, labour and limited capital will be last to embrace this, and may face government pressure to maintain employment.
- Reliability and ""intelligence"" of virtual support has to be improved
- In 2030 this should be broadly available. The technology is almost already available. Solutions tailored to mining will likely show up in the upcoming years and with growing user acceptance the virtual support will be a reality in 2030, if not earlier.
- This goal is too anthropocentric, and could develop into a chokepoint that slows advancement. It would be better to focus on extracting ore (with or without processing in situ) from a purely machine system perspective, excising the "human ghost" that has driven mining equipment and mine layout design from the very beginning.
- The entire mining operation should be hazard free and devoid of environmental pollution Above all, the concept of sustainability should be focused in all types endeavours.

Realisation date		**Research requirement**		**Tech. challenges**		**Future impact**	
Today	11%	Applied research	28%	low	4%	low	9%
2030	48%	App and some basic	61%	mod	32%	mod	30%
2040	15%	Subst basic res	11%	high	55%	high	35%
2050/	26%			v high	9%	v high	26%
Never	0%						

Prosperous Europe

„In suitable formations mining is done by small autonomous robots without creating large cavities"

- This development would be suited for e.g. mineral bodies, however, these robots need to be capable also in case of displacements of different size ---> need for knowledge on local geology, but also "geological intelligence" that is required for autonomous (!) mining. This technique requires very strong batteries that are strong enough for such heavy work. Once this technique is established, it can be applied in depths up to several kilometres. The robots and background equipment requires adequate materials that resist the heat of the depth, so this development requires already the availability of specialised alloys and their components (special steels etc.)
- Swarm robotics, autonomous operation
- Robotics in the construction of mining machinery, complete remote control of machines. Transport of small amounts of material over large distances and through irregular spaces.
- Robot Fleet Management, Swarm Intelligence
- Geological autonomous characterization. In situ ore processing. Coordination algorithms for collaborative robots
- Robots need to be robust and powerful, communication with the device might be problematic (under certain conditions), how to deal in case of unexpected failures.
- I like this idea very much: no big shafts anymore. Less energy, less waste rock and less subsidence at surface. Robots follow the rich metallic veins underground.
- Miniaturize the instrumentation for mining exploration and research in order to avoid the creation of large cavities
- Prior in-depth 3D knowledge of rock formation and their individual and collective engineering properties to design proper mining chambers without much of roof support but stable under conditions of proximal drilling and blasting vibration. Online modification of mine openings to follow the main ore bodies.
- Energy efficiency of autonomous devices have to be increased significantly. autonomy of robotic devices has to be increased. efficient ways of collaboration between different kinds of robots have to be found"
- This step will be a follow up to the first question. Consequently, i foresee this step about ten to twenty years later. Here, the main challenge is the adoption of the knowledge gathered and developing new mining concepts together with new machines."
- This is partway to the goal of fully autonomous, no-humans-underground, mining. Non-terrestrial mining needs this capability in the near future, and might benefit more from the low-and-slow approach than terrestrial mining (until the concept is proven).
- The use of robots may be experimentally started in open cast mining for the purpose of blasting or shovel operation, In underground mining operation the robots may be used for filling up process ie cut and fill process.

Realisation date	**Research requirement**	**Tech. challenges**	**Future impact**
Today 4%	Applied research 15%	low 4%	low 4%
2030 30%	App and some basic 65%	mod 11%	mod 33%
2040 24%	Subst basic res 20%	high 50%	high 39%
2050/ 42%		v high 35%	v high 24%
Never 0%			

Prosperous Europe

„Autonomous, ICT-controlled bio-mining is a leading production method"

- …Very reliable sensors are needed for continuous control measurements. This technique allows to use low-grade ores with limited env. impacts. However, the low extraction rate means that significant additional mines need to be explored for future supply, thus the overall mining footprint would grow.
- As recent examples in Finland have shown there are problems but bio technologies do have a great future.
- Will not happen. Autonomous development of such systems would comprise a significant danger to out environment. Therefore, society will not agree in the foreseeable future.
- Biological information extraction, sensing or/and gathering methodologies. Biological processes for ore or rock processing discovery
- Large-scale operations by biomining, functioning of bacteria in high-temperature environment, bacteria resisting toxic metals
- Today, there are almost no bacteria cultures know which show a significant "production rate", bio-mining will always remain a niche technology for very special applications
- Development of self regenerating and survivable bacteria under both aerobic and anaerobic conditions with the specific task of bio leaching either a single or multiple elements from a single solution. Depending on the conc, of the metals single or multiple stages of extraction can be thought of
- … the pradigm shift from mechanical to chemical mining is not something that appears to have been taken up at a broad scale. Similar attention would need to be paid to legacy issues of automated, ICT controlled bio-mining so that decisions reflected the true long terms costs against short term gains. Questions of responsibility in autonomous systems are another area that requires careful examination, particularly with regard to risk management and potential systems failures.
- There has to be a breakthrough to create organisms which process metals with a speed much higher than today.
- Bio-mining is not the panacea that it may appear to be at first glance. The high degree of wastage (to human eyes) and the very slow pace of bio-evolution are likely to limit this approach to special cases. And even then, we do not understand the inter-relationships of life and minerals sufficiently to be able to avoid long-term unexpected problems. This is not likely to become a "leading" method of minerals production, and until we have advanced much, much farther in our understanding of the "web of life," it should not be.
- The use of bacteria may be taken up in large scale operation like that desulphurisation of coal strata as practiced in certain cases. The research should be augmented so that bacteria may be used to detect Gossan Zones or removing arsenic in sulphide mineral paragenesis.

Realisation date	**Research requirement**	**Tech. challenges**	**Future impac**
Today 0%	Applied research 9%	low 4%	low 11%
2030 16%	App and some basic 55%	mod 7%	mod 18%
2040 33%	Subst basic res 36%	high 45%	high 35%
2050/ 31%		v high 44%	v high 36%
Never 20%			

Prosperous Europe

„Collaborative robots in-situ process ore deposits"

- Collaboration between requires unrestricted interoperability (and thus data exchange standardisation) between the diverse robot types and generations (otherwise it would become very costly). Ultimately, this can mean that men are not needed anymore underground for the mining of underground mines. The reliability of the overall system needs to be very high as technical errors can be very costly, but also dangerous. They would require as least as high security standards, as long as men are collaborating with the robots underground.
- There is already evidence of thoughts to minimize transport by some kind of processing underground, even if basic separation. Robots may not be in place, underground processing facilities of some sort will definitely minimize the environmental footprint
- Sensors for high quality and quantity measurements regarding different types of ore deposits: geochemical and geophysical methodological improvements
- The combination is interesting but would require rather large than small robots.
- as mentioned before, automation on quotidiam tasks is a must in order to avoid health and safety problems, risks. Change of minds needed to push it.
- Study of mining methods to low volume efficient ore processing. Geology characterization, and metallurgy characterization methods developed
- Sensors and information gathering methods for last mentioned issue. Robotics very developed. Mechatronics and robot material very robust and energy harvesting or underground generation.
- Robots capable to make works in related with in-situ processing of ore and to have the capacity to distinguish different types of minerals
- Self repairing/ self modification of hardware for chaning task with small size high energy/capacity batteries
- When you break or frack the ore you have a volume increase. What do you do with the excess mass? I do not see a way of a perfect in-situ process by robots underground. The only way is in-situ processing from the surface.
- Near-to-face beneficiation and underground processing is already available.
- This step will be likely to be realized together with the small autonomous mining machines. The challenges are comparable.
- A very worthy goal. This will be the point at which the "human ghost" has been nearly or completely removed from mine layout and scheduling. What remains will be to increase the pace of production from prototype to full systems.
- These may be used where large scale overburden is removed, bur on the contrary, the overburden has sufficient economic importance like that of Nickeliferous laterite, as recorded in Chromite deposits, housed in ultramafic rocks.

Realisation date	Research requirement	Tech. challenges	Future impact
Today 2%	Applied research 23%	low 5%	low 5%
2030 20%	App and some basic 61%	mod 18%	mod 23%
2040 34%	Subst basic res 16%	high 38%	high 45%
2050/ 44%		v high 39%	v high 27%
Never 0%			

Prosperous Europe

„Deep mines can be controlled and operated from anywhere"

- Remote control and remote operation depend on very sophisticated mining technology with autonomous robots (regarding these pre-conditions, see statements given beforehand). the control from other areas of the country or other cities requires additionally extremely stable internet connections that are fully protected against industrial espionage, or other spying and manipulation. The connection also needs to be protected against natural desasters…
- Automation should be double or triple redundant if remote control is to be implemented real time decisions support systems, condition evaluation, etc should also be in place
- Improvements for smooth and continuous communication and data transmission mainly by wireless networks
- Difficult to cover the whole processes on mining but some tasks can be performed on that way to reduce the risks and to change the social conception of a mine
- This is, in fact, partly realized in some mines already. Once the information reaches surface there is no problem to send it anywhere.
- Rock mechanics problems associated with laneway deformation, stresses of mining structure by excavation
- Is already today reality, you can control operations via internet, at the far end of "total control", automation of all parts of a mine needs realisation
- Development of continuous mining in hard rock.• Development of unmanned remote controlled continuous mining equipment. • Development of techniques for remote controlled backfilling, techniques that match systems of remote controlled continuous mining• Development of techniques for automation of explosives charging, both for mass mining, selective mining and drifting.• Development of remote control of scaling equipment and automated scaling.• Development of techniques for an automation of loading and transport with LHD machines, also in small scale mining.
- Research about job content for personnel working in the Remote Operations Centres (ROCs). • Development of visualization system for ROCs, where the entire value chain can be seen and controlled.• Development of automated decision systems for ROCs, especially simulation of critical operations.
- While there is already talk of the shift to "log in, log out" mining (from fly in fly out or drive in drive out), the social drivers need greater exploration. What are the benefits of controlling and operating mines from anywhere in the world (presumably far form the mine itself)? How are these views goinf to be canvassed in society or will expert knowledge be the driver here? …
- Is already a reality in some modern mines (e.g. Kiruna Mine, LKAB).
- Actually, this needs a very sophisticated technological approach. … We have to deal with wall rock alteration phenomenon and their corresponding signal that changes with depth.

Realisation date	Research requirement	Tech challenge	Future impact
Today 18% 2030 35% 2040 20% 2050/ 25% Never 2%	Applied research 34% App and some basic 59% Subst basic res 7%	low 11% mod 32% high 32% v high 25%	low 14% mod 23% high 40% v high 23%

Prosperous Europe

„Self-repairing robots reduce downtime"

- Self-repairing could be understood at least on two levels: microscopic repairs of coating or material damages, or actual repairing of functional units (with screws and riveting etc.). In particular the repairing of functional units requires drastic developments in artificial intelligence. Pre-condition for such a scenario is the establishment of autonomous mining robots (only then the effort for self-repairs could be considered reasonable).
- …this demands tremendous infrastructure both underground and the surface. Perhaps clear pathways, i.e. raises dedicated to moving parts between surface and underground (i.e. store on the surface and distribute underground pretty much like an autofactory
- For continuous and smooth self-repairing in general the entire system of the energy and raw materials must be changed fundamentally parallel with the smooth data transmission and communication, and supervision by human.
- Human expertise nature is mandatory in repairing actions (in physical or digital appearance through 3D reality).
- Condition monitoring and control technologies, prognosis technologies
- There is a big amount of work in autonomous robots that could repair their selfs very modular robotic devices would be necessary
- Total autonomous machine surveillance, preparation of self-repair, will be possible in certain cases, will not be possible in severe cases because at least the control unit must be intact in order to "control" repair
- An important challenge would be the development of robots which will be easily to manipulate but also which will be self-sufficient to repair any fail of their own mechanism so as it will not be necessary to have staff control them, this will reduce time and costs
- Development of advance metalloids (metals with very high density carbon fibers or plastics) and cermets (ceramic mixed with metals) with possible memory effect that can be triggered by electrical or thermal impulses
- Basic self-healing processes, new types of material (nanotechnology), types of artificial autoimmune systems
- Depending of the definition, this step can be realizable in 2020 or 2030 for small parts of the machine. However, this step is more desirable for autonomous machines and therefore I see it as a follow-up to the autonomous mini mining machines. It will take a lot of additional development work, e.g. regarding artificial intelligence or expert decision systems and of course mechanical/electrical engineering. Therefore, I foresee the real realization of this not until 2050.
- This will have two parts: Self-repair under close supervision (the humans-in-tight-control model), and self-repair as part of fully autonomous operation. Perhaps experience with the first part will make letting go for the second part easier. "Self"-repairing also refers to team-repair.

Realisation date	Research requirement	Tech challenges	Future impact
Today 0% 2030 11% 2040 20% 2050/ 64% Never 5%	Applied research 11% App and some basic 55% Subst basic res 34%	low 5% mod 7% high 36% v high 52%	low 9% mod 20% high 39% v high 32%

Prosperous Europe

„Deep mines are self-contained ecosystems operated by autonomous, self-replicating robots"

- This sounds like the ultimate vision, like possible future mining societies on Mars etc. It would require fantastic deposits that contain all elements required for all mining activities, i.e. any materials needed for any kind of tools and control devices (alloys, steels, rare metals). The effort to prove the feasibility of such a vision sounds unrealistic simply by the fact that providing the material basis for the technique, and the energy, is much more easy via mine shafts (from the Earth´s surface)
- I could easily answer never, but never is restricting. A replicating robot should be able to create a new generation by fixing the ""problems"". This demands a good bit of AI
- Challenges are high in many levels and success is not evident. Dangerous and unpredictable nature of the surroundings pose a serious challenge on how the robot may supervise in safe terms autonomously a potential deep mine
- Sounds Sci-Fi and I hope this will never happen.
- Biobased robots?, supply of energy, the ethical issues of bio+ICT+ecosystems. The meaning of self replicating? If they are the artificial humanrobots in the own ecosystem, the issues of control vs. slavery? Ethics may be the one of the key issues in development.
- The mine as an autonomous system is a challenge, the mine as an ecosystems is an even bigger challenge, almost every single part of a mine must be reassessed according to the applying eco standard - hard but possible.
- Very large source of energy, stable and self replenishing bacterias and newer hydro metallurgical processes specially for REE and the MPG (platinum metals)
- An understanding of the perceptions of this approach to mining and the relation mining has to humanity will be critical - particularly the environmental and social consequences - and how this form of mining supports/connects to our lifestyles.
- Working framework for self-replicating robots including also research related to self-healing and co-operative robotics
- This is scenario that is, at least for me, a couple of decades beyond the aforementioned ones. I do not see it to be realizable in this century. The social impact will be very high, but mostly as the respective technologies will be applied everywhere, reducing the overall amount of human work needed significantly.
- This is a crucially important long-term goal. Reaching it will require a much deeper understanding of the aggregate effects of complex systems than we currently possess.
- This particular aspect is difficult to achieve. However, in nature everything is regulated as a system. Accordingly, we hope to understand the self contained ecosystem of deep mines. Once, it is understood, self-replicating robots can function automatically. what is more important to understand the oceanic ecosystems, the ecosystems of the mantle plumes, the ecosystems of the convergent plate boundaries. it is also important to understand the distribution patterns of rare earths, which might control the ecosystems as a whole.

Realisation date	Research requirement	Tech challenges	Future impact
Today 0%	Applied research 14%	low 7%	low 9%
2030 0%	App and some basic 37%	mod 0%	mod 7%
2040 9%	Subst basic res 49%	high 16%	high 26%
2050/ 63%		v high 77%	v high 58%
Never 28%			

Prosperous Europe

Other relevant ICT

- Robust communications. Real time underground GIS mapping and updating. Real time sampling of ore for proper processing - different processing queues can be available depending on the type of ore.
- Mines should remain essentially human-controlled. Robots should be developed to operate in remote and dangerous sectors. They may become autonomous to some extent, but not self-replicating and not completely removed from human control.
- The cost and expenses of the visions? Are they going to be in use some day, or is the human working still low cost production route? Dark Vision: Biobased robots, artificial intelligence when a robot is coming a human being? Ethics in developing too intelligent biobased "robots" and the closed ecosystems. Self-replicating robots will form new breed, that is not ethical to control? Positive Vision: The ICT possibilities in serving the deep mining in guidance of sustainable society, no need of dangerous human work, only limited areas are mined, no environmental harms, the place of the mining is returned into natural stage afterwards. "
- Communications, reliable autonomy, human in the loop operation, learning, robotic hardware, robotic drilling or mining, high-efficient drilling.
- My opinion is, that the "automatic mine" is a real future possibility. It must only be wanted!
- A robotic - human interactive relationship, through a collaborative ambient, to elaborate and revise mining plans and operational strategies. A strong communication system that allows to virtually ""be present"" at mine site for professionals in charge of the ""autonomous"" operations.
- The most important issue as to ICT for underground mining will be reliable communication through the entire mine, the reliable monitoring of all kinds of conditions (environment, machine movements, machine conditions, machine operation, etc.). The communication and information network must ensure information being present at all places in a mine at the time required. The factory of the future (above ground) should be applied to the underground factory as well.
- A concept that has already been partly realised (in Swedish mines and elsewhere) is three consecutive phases to ensure safe underground mining. The first phase means that all work is done from vehicles that have safety cabins that prevent injuries from falling rock, but which may also be provided with substantial comfort. The second phase means that staff is moved to secure control rooms where they are remote monitoring and controlling the different operations. In the third phase, we have a production with zero entry for employees based on comprehensive automated systems.
- Designers of ICT hardware must make multiple visits to present days deep mines of both regular and irregular ore bodies. They must also have a in depth knowledge of both rock mechanics, geothermal conditions, electromagnetic/telluric current system along with radiation hazards to come up with sustainable robust as well as miniature designs of modular multifunctional parts of robot system."
- The trend to invest in new mines only if they have a cost structure in the lower third (lower third rule) or at least below the world wide mean leads to more and more cost effective mines. If Europe wants to beat this with deep mines and probably deposits with not so good grades there have to be major breakthroughs for the development of very cost effective deep underground mining systems, meaning the investment and operating costs have to be significantly lowered.

Fragmented Europe

"Dangerous and heavy tasks are no longer performed by humans underground"

- It depends how you define dangerous. Some underground tasks will always be dangerous.
- Broadband communication networks are required. Maintenance of complex systems underground may be an issue
- Requires a broad range of automation and tele-presence technologies to replace human presence in underground mines. Requires robust solution of the problem of digital broadband communication in complex underground mines. Safety may actually deteriorate during implementation of new technology with a mix of human and robotic operation. Cost of new technology may initially allow its use only in the largest mines. Small mining operations and those working marginally economic deposits may never afford the capital required to install such technology. Widespread introduction may require legal underpinning to make human presence in active underground mining operations unlawful.
- Again, in the EU, we have the privilege of worrying about such things but it will be cheaper to employ uneducated labourers in developing countries to perform tasks that in the E.U. are considered heavy
- Monitoring and control of mine conditions. Surveillance and statistical support in mining injuries, fatalities, and disease. Material and structures testing to prevent failures and accidents. Advanced training tools for mineworkers (e.g. 3D virtual environments)
- Heavy duty and dangerous tasks are already being automated nowadays, not only in mining. In many cases, technology already exists to perform and control the operations from a safe distance. Improvements with respect to monitoring, data communication and augmented reality are needed to transfer these technologies to demanding (dust, moisture, temperature, gasses, corrosive fluids) environments encountered in deep mines. Furthermore, the technology need to be properly tested and reliability proved before it will be applied in - the conservative - mining industry.
- Robotics, which in turn implies sensing, communication between robots, interaction between robots and the physical world, organising robots, portable power, navigation in underground GPS denied environments, etc. The precondition is that the total cost of "ownership" for human labour, including the cost incurred due to accidents, is larger than the total cost of ownership of a robot with equivalent capability.
- Robust vision & robotics will be needed. Funding is improper for high-risk technical development.
- It may not be true for all mining countries in the near future. A Europe-specific method should not result in a mineral product far costlier than similar minerals produced elsewhere. Besides, socio political dimensions in respect of employment generation and levels of skills will vary from country to country outside Europe. Finally the education institutions should be ready to accept it and include it in their teaching curricula. Total on-the-job training will increase the cost.

Realisation date	Research requirement	Tech challenges	Future impact
Today 0%	Applied research 15%	low 4%	low 4%
2030 46%	App and some basic 85%	mod 38%	mod 38%
2040 27%	Subst basic res 0%	high 46%	high 50%
2050/ 12%		v high 12%	v high 8%
Never 15%			

Fragmented Europe

"Virtual support staff in augmented reality is available in deep mines"

- Extensive broadband communication networks, specifically adpafted to the mining activity, will be required
- Requires more detailed 3D modelling, reliant upon surveying and geological data capture together with some improvement in modelling technology, with full integration of 3D geochemical, geotechnical, and mine infrastructure models. It also requires improvements in underground data communications.
- Before virtual support staff become a reality we need to understand the unpredictable nature of real mineralisation a lot better
- Augmented reality could have a major impact by speeding up the decision processes. Again, this could bring an increase in productivity and a fall in operation costs in the mining operations.
- I believe that the critical items to consider when implementing an augmented reality system will be: a) the need to set up instruments in the objects that will be evaluated, and b) the decision of which objects to consider.
- Virtually the same remarks as those made in the previous statement are relevant here. Challenges are bit higher as the support stall asks for a strong degree of robotisation and some level of artificial intelligence to operate in a semi-autonomous way and/or to communicate with other actors in the mine. Development changes however remain largely related to sensor and communication equipment and the selection of materials/solutions that are adapted to the demanding environments met in deep mines.
- Good ways are required to bring the environment to the virtual support staff member: through visualization, interface design etc. Tools are required to allow virtual support staff to interact with the reality underground.
- High speed communication between data servers and augmented reality device. Programming of virtual support staff for correct response to humans. Monitoring and sensor system for support staff algorithms
- I envision two fundamental challenges. First, the development of compact wearable, and not energy-hungry devices. In this respect, further research on energy-harvesting technologies is required. Second, the development of the next-generation communication infrastructure that is widely available in the mine and enables for datarates that are higher than today. The latter condition is fundamental in order to handle the flows of data to and from the miners and the control centre.
- Availability will be a slowly developing scenario. The industries may resist initially and their acceptance will be of paramount importance followed by that by the educational institutions.

Realisation date	Research requirement	Tech challenges	Future impact
Today 4%	Applied research 31%	low 12%	low 19%
2030 57%	App and some basic 65%	mod 61%	mod 42%
2040 19%	Subst basic res 4%	high 12%	high 31%
2050/ 12%		v high 15%	v high 8%
Never 8%			

Fragmented Europe

"In suitable formations mining is done by small autonomous robots without creating large cavities"

- This will certainly happen soon. Driven by the need to create mines with minimum above-ground impact, mining and a lot of mineral processing will be underground. Continuous mining, processing and back-filling of mined regions will mean that large cavities will exist only temporally. Why "small" robots? Robots of all sizes will be used.
- How autonomous can a small robot be assumed to be? Its main function would be extracting the raw material. If processing in-situ to extract metals these would need to be transported to the surface - by another class of robots, or by existing conveyor technology? Battery power would at present be a severe limitation, hence basic research needed. Efficient operation would require collaborative robots. Bulk raw materials (e.g. salt, potash, gypsum, limestone) cannot be extracted without leaving large cavities. These could possibly be backfilled with wastes from elsewhere, but the geometric problems would require careful mine planning to ensure that reserves are not made inaccessible by such backfilling. The long lead time for the development, and the basic research inputs required, would necessitate national or multinational government research funding
- Utilization of new energy sources, miniaturisation in energy storage
- Small but extremely valuable and rich zones of mineralisation in difficult environments could become economically viable if robots could mine them - but there remains the question of how to power the robots
- This could increase our ability do to selective mining, with a substantial costs reduction, in the mining and in the concentration operations. I think that this could be achievable on the long run, because the equipment used to these operations must be very reliable and the methods to support the underground development must be adjusted/changed.
- This goes a step further as it asks for autonomous operation of fleet of robots that need to work together under demanding conditions and that need to be able to keep themselves going (auto-assembly, auto-reparation, low energy consumption/own power generation). In order to realize this statement, the robots (or fleet of robots) need to be able to process information gathered from various sensors and react on it on its own (at least to some extent). Fast and reliable data transmission between the underground and a surface control room will be needed to intervene in order to handle unexpected situations. Moreover, energy consumption of the robots should be minimised or own power generation solutions developed to extent autonomy… It could bring us close to a situation of zero-impact mining.
- Non explosive rock breaking techniques suitable for small machines, or a reliable and safe way to place explosives using small machines. Dealing with high reaction forces in light machines. Coordinating between a fleet of small machines, and communicating sensing data.
- Extraction creates cavities. It is impossible to extract only the valuable ore by mechanical activities.

Realisation date	Research requirement	Tech challenges	Future impact
Today 0%	Applied research 12%	low 4%	low 0%
2030 28%	App and some basic 52%	mod 24%	mod 40%
2040 44%	Subst basic res 36%	high 28%	high 28%
2050/ 20%		v high 44%	v high 32%
Never 8%			

Fragmented Europe

„Autonomous, ICT-controlled bio-mining is a leading production method"

- In-situ leaching methods will be more important, not necessarily bio. This will all be part of the drive to have most of the mining and processing done underground
- Although bio-leaching technology has already been developed, the widespread use of bio-mining for a wide variety of raw materials would be dependent on extensive further basic research. There are serious safety concerns if the bio-agents are released into the environment for bio-mining: for example the risks of groundwater contamination, the possibility of dangerous mutations, etc. Also it is not clear how ICT would actually control the bio-mining process and constrain the bio-agent to conform with a defined mining plan. Much more likely (2030-2040) is the development of bio-agents for metal extraction as a replacement of existing mineral processing technology. This could involve small-scale (perhaps mobile) digesters located underground, close to the mining, and returning waste to be used as backfill.
- This could happen only in a far future, because the less developed countries will have a major barrier to obtain and use ICT technologies and equipments on mining operations (cost and safety concerns by developed countries will oppose the dissemination of the high tech equipments)
- Fully autonomous biomining seems very unlikely as some level of control will be needed to steer the biologic agents and to avoid spill over to the external (outside the mine) environment. Biologic agents are much more difficult to control than robots. It hence seems unlikely that R&D will strongly pursue this route when there are alternatives. A combination of robots with biologic agents to leach out/extract metals from ore under well protected/controlled conditions.
- Full autonomy represents a huge challenge. In particular, using machines to fix machines (even if human controlled) is going to be a huge practical challenge in actuators, sensing, logic and control, etc.
- Selective solvents, deep rock cracking technologies, ultra deep flow control and process control.
- An increase of the efficiency of the biomining process is a fundamental requirement. From the ICT side, the development of ad hoc sensors to monitor the state of the biomining process might be required. In this respect, a strong collaboration between electrical engineering and biomining engineering is envisioned.
- How to bring microbes into contact with a large percentage of the available mineral in situ in competent rock?
- Bio-security issues and public acceptance thereof.
- Application of ICT in bio-mining may not be popular right away because of its slow rate of production. bio-mining will become necessary when the quality of the ore is very low, it is deep-seated, it is located in an environment-sensitive area and alternative source of the same ore is not available at competitive price. However, its application may be called for in urban mining as soon as possible.

Realisation date	Research requirement	Technological challenges	Future impact
Today 0%	Applied research 12%		low 12%
2030 15%	App and some basic 53%	low 4%	mod 27%
2040 23%	Subst basic res 35%	mod 15%	high 42%
2050/ 35%		high 43%	v high 19%
Never 27%		v high 38%	

Fragmented Europe

„Collaborative robots in-situ process ore deposits"

- This is a combination of the small autonomous mining robot, in-situ (maybe bio-) processing, and very advanced network computing. The power requirements would require very advanced battery technology to be developed. All depends on how small the robots are considered to be. If sub-centimetre scale, my opinion is that this would be neither feasible nor economically desirable, even as an objective, for the next 30-40 years. If metre-scale, then this could be developed as an evolutionary step from the tele-presence / augmented reality environment, with applied research to establish the communications standards and protocols needed for a network of collaborative robots sharing a common mine production plan.
- Processing ore on site would be of huge impact for remote areas but it carries very substantial challenges as ore changes in physical properties, even within one mine and the expertise by the mill personnel has a lot to do with intuition and not with science and technology
- The need to reduce the risk of loss of human lives is a strong driver in the mining industry (and at other civil applications such as fire fighting) and in the military industry. I suppose the military industry has made strong progress in this area, and so the adaptation to the mining industry will probably lacks just applied research.
- Different robots working together to complete complex tasks are a likely development that can build on ongoing R&D in the field of communication and automation. It asks for proper standardisation (both with respect to hardware and software protocols/data types) that should allow that robots can readily interact with each other. As already mentioned in previous statements, the ongoing R&D should be translated to the demanding environments met in deep mines and should be properly tested in order to prove the reliability of the technology.
- collaborative algorithms, server or distributed based control, fast communication a process of data
- Coordinated manipulation, cooperative transportation if needed
- The main challenge regards the development of a distributed intelligence that enables the collaboration between robots. Afterwards, the control algorithms must be carefully tested on site.
- Underground communication and telemetry.
- Power supply and distribution.
- Impact on costs of end products should be worked out. It should remain globally competitive. The cost of training personnel should also be worked out.
- Requires understanding different modes of joint activity, roles, improvisation, etc. involved in collaborative work. If it is simply meant that automated systems are coordinated, that is occurring today.

Realisation date	Research requirement	Tech challenges	Future impact
Today 4%	Applied research 17%	low 8%	low 4%
2030 25%	App and some basic 54%	mod 17%	mod 33%
2040 25%	Subst basic res 29%	high 46%	high 50%
2050/ 42%		v high 29%	v high 13%
Never 4%			

Fragmented Europe

„Deep mines can be controlled and operated from anywhere"

- This is already being done in Australia and elsewhere.
- May be not all operations can be remotely controlled. Some will still require human intervention: geological surveying, maintenance.
- Already achieved, in part. In 1997 I saw a demonstration of remote operation of North Parkes Mine, NSW, Australia from a lecture theatre in Perth. Human involvement in mining has not been eliminated yet, though this is probably achievable with incremental development of robotic technology. Ultra-deep mines are a different problem - with high temperatures and geotechnical problems ruling out any human access to mines deeper than about 5000 metres. This would require serious technological development - hardened robotics and robust communications solutions, for example.
- The problem is less operating deep mines than finding new very deep mines without a surface expression of the ore
- Improving of communication and scanning technologies
- The need to reduce the risk of loss of human lives is a strong driver in the mining industry (and at other civil applications such as fire fighting) and in the military industry. I suppose the military industry has made strong progress in this area, and so the adaptation to the mining industry will probably lacks just applied research.
- The mine of the future project of Rio Tinto and similar initiatives in e.g., Australia and Scandinavia prove that remote control of mines is already possible. Additional - mainly applied - R&D with respect to sensors, augmented reality and fast and reliable data transfer in the underground working is needed to take remote control of mines a step further.
- My answer here assumes that deep mines can be controlled from surface. If that is done, the step of controlling from elsewhere is minor.
- I think you can do that today. What control means exactly?
- Communications, tele-presence
- The present ICT infrastructure enables for high datarate broadband communications from the mine surface to everywhere in the earth. Therefore, the mine monitoring activity can be performed far away from the mine site. A fundamental precondition is the possibility (and the willing) to access to expensive communication solutions (as satellite communications).
- Reliability issues with underground equipment.
- Cost-wise the remotely operated mining methods should be competitive globally. Depth is not the only criterion, the price of the mineral and the size of the deposit are also important.
- Operations will always require some degree of local maintenance of automated systems, until this also is automated.

Realisation date	**Research requirement**	**Tech challenges**	**Future impact**
Today 25%	Applied research 46%	low 17%	low 8%
2030 25%	App and some basic 46%	mod 46%	mod 59%
2040 29%	Subst basic res 8%	high 29%	high 25%
2050/ 17%		v high 8%	v high 8%
Never 4%			

Fragmented Europe

„Military and mining research on robotics is performed in the same research centres"

- Security and terrorism risks, IPR loss, geo-political tensions
- MILITARY AND MINING RESEARCH ON ROBOTICS probably is already happening in some countries but will never happen in others.
- Hardening of robotics is a requirement common to both military and mining applications. However, the sort of hardening required is different for the two. In fragmented Europe the military research will be better funded, so the mining industry may see it is a more cost-effective option inn the short term.
- Mining research has much more in common with space exploration
- Recognition of military as a major driver of technological innovations
- The need to reduce the risk of loss of human lives is a strong driver in the mining industry (and at other civil applications such as fire fighting) and in the military industry. I suppose the military industry has made strong progress in this area, and so the adaptation to the mining industry will probably lacks just applied research.
- Raw materials (and our lives) will be controlled by governments and military - not good.
- There are clear parallels between the characteristics of military robots and the needs in mining: autonomy, remote control, robustness. It is likely military developments will find their way into the mining industry.
- Military applications of robotics are always prior to any other application. Military technology could be implemented into other sectors.
- Due to political issues this is very unlikely. It would mean severe intrusion of politics / forces into economic agenda, which is unrealistic in the selected scenario.
- A fundamental pre condition is the willing of the military world to offer their knowledge and infrastructures to the mining world. This would significantly improve the quality of the mining research with substantial benefits for the whole community.
- Underlying technologies often have multiple applications - IP issues.
- The core competency of the military research laboratory is altogether different from that of mining. Military research is based on predetermined situations while mining situations are invisible and unpredictable.

Realisation date	**Research requirement**	**Tech challenges**	**Future impact**
Today 17%	Applied research 35%	Low 38%	low 17%
2030 17%	App and some basic 44%	mod 13%	mod 22%
2040 13%	Subst basic res 17%	high 41%	high 48%
2050/ 13%		v high 8%	v high 13%
Never 40%			

Fragmented Europe

„Disabled people, senior citizens and teenagers are routinely employed by mining companies (via novel tele-working solutions)"

- Re-thinking mining by moving away from virgin raw material extraction
- Is this not already happening? It all depends on the significance placed on "routinely"
- Adequate training can be a limitation for some groups of people (elderly people)
- Gaming type interfaces may allow this. However, letting teenagers loose on such expensive equipment as in a mine - which may progressively become less accessible to human technicians to fix - is likely to be a risk too far. Nevertheless, disabled and senior citizens (especially those who formerly worked in the industry) will become an important part of the workforce.
- Identify the critical tasks compatibility with the hardware/software platform
- This is a likely development (especially for older employers) in case mines become remotely controlled. In combination with augmented reality and artificial intelligence, the expertise of older experts can be readily integrated into the actual mining activities - where nowadays, such experience is lost as the elder people are no longer fit to work in the mines -. This could be an important development in the light of higher age of retirement.
- Basic research as given above does not mean the technology, but social / ethical / societal research & development.
- Reliability and dependability of in-situ machinery, autonomy (intelligence), communications
- Beside the technological requirements, as the automated mining operations or the underlying communication infrastructure, people must be extremely skilled on mining activities. Therefore, training is an important issue that, probably requires in-field experience that is not easy to be performed by a such target.
- Mining companies are conservative by nature so changes to workforce demographics will need to be shown to be effective before adoption.
- Designs have to be special depending on the kinds and degrees of disability

Realisation date	Research requirement	Tech challenges	Future impact
Today 10% 2030 20% 2040 30% 2050/ 35% Never 5%	Applied research 20% App and some basic 55% Subst basic res 25%	low 20% mod 35% high 25% v high 20%	low 20% mod 15% high 40% v high 25%

Fragmented Europe

„Other relevant ICT"

- Sensors to measure ore grades and physical properties of rocks in mines must be developed. Sensor on drill bits to provide real-time information of the rocks being penetrated. A means to feed this information to the mining "robots" will need also to be developed.
- Automatic mineral mapping will be required to perform selective mining in some types of deposits
- Standards. Scalability to small deposits. Detailed modelling. International standards will become more important as data integrity is crucial for increasing reliance of operations on ICT
- Apart from running existing mines more efficiently, the main use of ICT will be in data processing in mineral exploration in extreme environments
- Remote control and operation of deep mines. Teleworking solutions- Complex systems management.
- Standardization: it is likely that different robots/technologies will have to work together in order to complete complex tasks; exchangeability of parts could make robots more robust/increase autonomy
- Energy efficiency and efficient energy storage options (battery technology, fuel cells, ...): needed to increase autonomy of robots"
- Modelling: mines are complex 3D bodies, defined by irregular geometry of the orebody. Being able to visualize what is known, and model what is supposed in a very clear, very user friendly way, would allow for better and faster planning.
- At the moment, the planning phase lasts several months to achieve a year of planning. This has to be brought down to a live plan, always applicable, always up to date with reliable data. It must be very easy to do ""what-if"" scenarios in the planning/modelling tool.
- Integration - everyone needs to use the same body of data, and plan in the same tool. At the moment, each discipline has its own tool leading to big issues of data integrity, and making integrated "what-if" modelling very difficult.
- Secure - encrypted, no data loss - wireless communication between devices. Communication must be fast, data process must be fast as well. Special sensors for monitoring. Sensor installation has to be proper.
- Communications and perception will be key for future automated machinery and their tele-operation or tele-supervision
- ICT will be extremely important a) for the localization of the miners, b) to improve the safety levels in the mine, and c) to support the rescue operations.
- Scheduling, mining efficiency is heavily dependent upon logistics. Adaptive real time scheduling of resources taking into account equipment down-time and deviations from planned progress could have a significant impact. Surveying - Automated laser scan surveying as the mine is developed for comparison with the mine plan.
- Cost-wise the ICT-based exploration and mining methods should be competitive globally. Natural resources defy any logic with regard to their size, depth, quality and a great many other characteristics which determine their exploration, extraction, processing and utilization. Hence the scope of application of the ICT as well as the break-even costs vis-a-vis conventional methods should be clearly defined. Presently known deposits in Europe where ICT can be applied without sacrificing the competitiveness of the mineral vis-a-vis other mines of the same mineral should be identified.

As the deadline for completing Delphi Round 1 was very close to the Brussels workshop, it was agreed that launching Delphi 2 before the workshop would be impractical (i.e. Round 2 of the survey would still be running during the implementation of the workshop). Instead, it was decided to use the Brussels workshop as an opportunity for the evaluation of Round 1 results, taking advantage of the multidisciplinary expertise present for that meeting. The conclusion within the consortium was that the benefits (expert group available for discussions) would outweigh the costs (further delays with implementing the survey).

Experts participating at the workshop in Brussels were asked to evaluate the first round of the Delphi Survey and to think about possible constraints in the future. During the evaluation experts were also asked to focus on areas that fall into the category of exploratory/basic research. This meant the "elimination" of certain topics that were considered by most of the experts as falling into the category of "applied research" or topics that were already under research/implementation today. These inputs were then used to formulate meaningful pre-conditions for the second round of the Delphi survey. Discussions considered different speed and rates of technology transformation, and eventually three main "scenarios" could be differentiated corresponding to expert expectations for the defined timeframe.

A. Mining technologies remain (essentially) the same, supported by more and more sophisticated ICT. This scenario is strongly represented by the following statement: *„Dangerous and heavy tasks are no longer performed by humans underground in Europe".*

The scenario corresponding to this statement describes underground mining operations that are not substantially different from today's processes. Emphasis is on safety and operating under increasingly harsh circumstances, relying on hardened and novel ICT applications (whilst the mining and processing methods would remain essentially the same). Novel ICT supports either remote operation (much more sophisticated than today) or it allows the co-existence of humans and (semi-) autonomous machines in the same environment. There has been strong consensus that this statement this could be achieved before 2050 (even by 2030). Several comments revolved around remote control solutions and a strong need to remotely monitor activities inside the mine. This statement could be slightly modified for Delphi Round 2 in order to specify the geographic location (Europe). This has been an important discussion point as several experts expressed their views about technological feasibility vs. economic realities in different parts of the world. Removing humans from performing dangerous and heavy tasks will eventually break down to economics (profitability and the total cost benefit ratio of such action).

B. Mining technologies co-evolve with novel ICT, resulting a partial paradigm change not just in the use of ICT in future mining operations, but in mining methods as well. Such paradigm change is especially strongly indicated in the following Statement: *„In suitable formations mining and (pre-) processing is done by small autonomous robots without creating large cavities"*

This paradigm change could be partial (valid for "suitable formations" only), and it is possible that the old paradigm and the new one co-exists in the same mine. Certain sections of the mine could become fully autonomous e.g. at extreme depths. These sections are closed off to humans, only accessible for machines, while at other levels mining is still carried out the "old ways" by both humans and machines. This statement has been recognized in all groups as a potentially emerging disruptive trend that could lead to a paradigm change in underground mining technologies. In this scenario mining and pre-processing would be carried out by autonomous units operating in heterogeneous swarms. Due to the swarm nature mining operations would become scalable not by increasing the size of the individual machines, but by adapting the number of units in the swarm to the size of mining operations. Bio-based analogues (such as underground and burrowing animals) could support the development of such new types of autonomous machinery. As a result of such paradigm change the entire mine (or a section of the mine e.g. at ultra-depths) would need to be re-planned so that the new design would no longer support human presence, but rather support machinery. Monitoring by humans was seen as desirable, but given the extreme conditions strong autonomy of the machinery will be required so that the machines could continue operate in the case of lost communications. It has been suggested that “minerals pre-processing” be added to this statement indicating the need to perform mining, pre-processing and possibly exploration as an interconnected action.

C. A complete paradigm change for mining methods and how mines are designed, a scenario, which is especially strong in the *"Deep mines are self-contained ecosystems operated by autonomous, self-replicating robots"* Statement.

The scenario corresponding to this Statement envisions a complete paradigm change, a „quasi” self-contained environment in which only the mined material (and some waste rock) leaves the mine. Humans are not present in the mine, which is designed to sustain machines only. This Statement greatly divided the experts, who participated in the first round of the Delphi survey; almost 30% of the respondents believed that this would never happen, others referred to the statement as a „crucially important long-term goal”. Experts in all three groups emphasized the relevance of this Statement for FET. It is suggested that this Statement be modified for the second round; the term “self-replication” being removed in order to reach towards consensus. Self-containment is generally understood as being “quasi” self-contained since material flux between the surface and the mine is inevitable (this is the ultimate objective of mining operations) but it has been acknowledged that the impacts would be minimum on the surface, and that the decisive proportion of the supporting activities (energy production, repair, even on-site partial manufacturing, etc) would be carried out in a closed cycle. If humans are completely removed from the environment then this opens up whole new possibilities in mine-design and operation, since the environment no longer needs to sustain human life.

There has been strong consensus among the experts that the above three “scenarios” all provide relevant challenges for FET, cutting through different emerging ICT areas. The expert inputs collected during the Brussels workshop were used to formulate key pre-conditions for the second round of the Delphi survey.

Note: further information on the discussions may be found in D 2.2. Report on the Brusels Workshop, and in D2.3 Report on the Foresight Exercise.

4.2 Round 2 results

Learning from previous experience (also informal feedbacks that indicated that shortening the survey would be beneficial), Round 2 of the survey was designed in a deliberately streamlined manner, where the objective once again was to generate comments for further discussions, and – in particular- the support the definition of call topics.

In an unorthodox manner, the Delphi Round 2 Statements were also used in a parallel survey addressing explicitly the FET ICT community. This was seen as beneficial as the initial Delphi was used to poll predominantly members of the mining engineering / earth science community (although workshop participants with FET/ICT background also participated). Receiving some additional comments by FET ICT experts was expected to highlight new areas, and also to help bridging the gap between the two communities.

The statements formulated for the two Groups were the same. The notable differences in the implementation were:

- Responses by the two groups were saved in different databases, allowing a direct comparison between Delphi Round 1 & Round 2 and between Delphi Round 2 & FET ICT survey.
- Different invitation e-mails with different contents were sent out to the two groups. For the Delphi Round 2 group a shorter e-mail was sent with a summary of the outcome of Round 1 and some key statistics. For the FET ICT group a more detailed e-mail was sent describing the objectives of the survey and the overall project background.
- Different Welcome pages were developed for the two groups - more details were provided for the FET expert group about the EXTRACT-IT project and its objectives.
- Different Last pages were developed for the two groups – FET ICT experts were provided a number of presentations and summaries on mining ICT topics
- Delphi Round 2 participants were provided all the experts responses from Round 1.

Besides the above differences both groups filled in the same survey (identical statements) and were provided the same scenario summaries.

The Statements and the Pre-conditions were formulated as a direct outcome of the Brussels workshop.

Invitation was sent out to Delphi Round 1 experts first on 19 August and to the FET ICT experts ten days later. Deadlines to complete the survey were extended to 16 September in both cases following an electronic reminder.

63 experts participated in Round 2 of the Delphi.

An additional 47 experts representing the FET ICT community gave their view in a separate survey, which was identical in content to Delphi Round 2. This additional survey was also anonymous. The following ICT experts agreed to publish their names as a "contributor to the survey":

1.	Dr. Eugen Meister	University of Stuttgart, Germany
2.	Prof.Dr. A.E. Eiben	VU University Amsterdam
3.	Prof Alan Winfield	Bristol Robotics Lab
4.	Ir. A.C. van Rossum	Almende B.V.
5.	Giuseppe Riva	Istituto Auxologico Italiano
6.	Prof James L. Crowley	INRIA Grenoble Research Center
7.	Pr. Nicolas Bredeche	UPMC
8.	Dr John Smith	centrog
9.	Prof. D.r Heinrich Bülthoff	Max Planck Society
10.	Dr. Rosa Di Felice	CNR-NANO-S3 Italy
11.	Dr. Stephan Stilkerich	EADS Innovation Works
12.	Carlo Pinciroli	Universite Libre de Bruxelles
13.	Prof. Alessandro Moschitti	University of Trento
14.	Giacomo Indiveri	Institute of Neuroinformatics, University of Zurich
15.	Thor List	Communicative Machines

16. Barbara Marques	ENP
17. J. F. Broenink	University of Twente
18. Dr Petros Daras	CERTH/ITI
19. Professor Lennart Karlsson	Alkit Communications AB, Sweden
20. Prof. Kostas J. Kyriakopoulos	National Technical University of Athens
21. Prof. Silvia Coradeschi	Orebro University
22. Dr Evert Haasdijk	VU University Amsterdam
23. Nikola Serbedzija	Fraunhofer FOKUS

Below is a summary of results, with some of the more elaborate/representative comments listed. The full database dump is Annexed to this Report

Group A – Delphi Round 2
Group B – FET ICT

Statement 1 ***"Dangerous and heavy tasks are no longer performed by humans underground in Europe"***

No. of responses Group A: 63
Probability of occurrence by 2050 Group A: 63.8%
No. of responses Group B: 47
Probability of occurrence by 2050 Group B: 70.6%

Precondition	Group A		Group B	
	Agree	Disagree	Agree	Disagree
Precondition 1 Human augmentation solutions are developed for underground mining (exo-skeletons, wearable robots, etc) for protection and to artificially increase human strength.	42	21	32	15
Precondition 2 Robotic companions (humanoid robots) are developed, capable of working alongside miners taking over dangerous and heavy tasks with minimal supervision.	38	25	33	14
Precondition 3 Specialised machinery are widely available that perform autonomously dangerous tasks capable of learning to solve new and unexpected challenges under harsh and dynamically changing conditions.	50	13	39	8
Precondition 4 Much more versatile telepresence options are deployed that allow the operator to merge and interpret information from several sources utilising new modalities for individual and group perception in augmented, virtual spaces.	61	2	43	4
Precondition 5 Wireless communications are developed that allow communications through hundreds (thousands) of meters of the rock and realtime information sharing between machines and humans both in the mine and between the mine and the control room(s).	43	20	29	18
Precondition 6 New (much more robust and versatile) sensors are designed and deployed supporting machine vision for navigation, production processes and interaction with humans.	60	3	42	5

Selected Comments to Statement 1 - <u>Group A</u>

- Underground Mining as such is already going on today in harsh environments. Considering the even harsher environments expected in the future, I don't think that highly complex but also filigree systems of human augmentation will be possible within the given time frame. However, systems based on improved and reliable communication as well as data processing and provision/visualisation will have a chance to be realised very soon. There will be a big need for such systems in order to improve attractiveness of workplaces underground as well as coping with the upcoming challenges.

- In our opinion the most important task is to design perception systems (sensors, self-monitoring, etc.) and data evaluation algorithms which are able to function under harsh environmental conditions, typical for mining applications. The currently available, state-of-the-art sensors (even ruggedized ones) are not able to operate properly in heavy mining conditions (e.g. directly at the face).
- I do not think it will be possible to develop machines to solve new unexpected dangers
- Working with sensors in deep mines is a challenge, because of the dusty, hot, wet environments (I have bad experiences with all kind of ICT tools in caves)
- Unless a dramatic context change happens (e.g. a third world war) this is a feasible scenario by 2050. It is important to stress that this scenario will only occur in Europe if it remains amongst the more developed areas of the planet. But this could change in one generation time, considering the economic crisis, the fall of births and the increasing emigration pressure from Europe's borders
- I believe that wireless technologies through rock will be developed by that time, but I am not sure that they will also have the bandwidth for real-time interaction. The wireless communication can also be setup between the different agents where they are used as kind of swarm to keep a dynamic network.
- Wireless transmission through rocks will be a major challenge in view of presence of telluric current, self potential effect and anisotropic nature of the rock media with joints, fractures and even in different water content makes them difficult for any radio frequency transmission.
- Aspects of all of the technological developments would be included, except for the human augmentation - which could under some circumstances provide temptation to increase rather than decrease human presence underground. Most likely is a combination of telepresence/teleoperation with new communications technology and semi-autonomous robotics. Development of sensor technology will be the key to success: in particular, non-visual sensors (rock-face chemistry and mineralogy through a range of spectrographic methods (X-ray, optical, ...) combined with an extensive database for mineral identification; standard use of microseismic detectors and strain-measurement everywhere to determine rock stability
- I am not expert in this specific area, so my responses are based on general knowledge of the field. Considering the progress in computing, sensing and manipulation towards higher autonomy of machinery and robotics. Much more basic research is required in cognitive robots and self-reconfiguration.
- There are cases when the morphology of the ore body may drastically change with depth, specially in cases of hydrothermal deposits. Accordingly, I believe that there should be more basic research to understand the geometry of the ore body, for hydrothermal sulphide deposits in particular.
- I think machines can be made to autonomously perform dangerous tasks. However, the ability to solve new and unexpected challenges is a bit questionable. E.g. the physical limitations of the robot may prevent this (e.g. if you are drilling robot you may not be well prepared for a water flood or some other disaster). I think given a range of possible scenarios robots that can handle them can be designed. But learning from scratch something that was not anticipated requires human help.
- The high energy requirements of exoskeletons will be prohibitive for this application in this timescale. There is already evidence from military applications of effective robot companions capable of carrying large loads (General Dynamics 'Big Dog'). In this timescale these are likely to be available and cost effective for this application.

- Robotic companions capable of carrying large loads are very likely in this timescale as they have already been demonstrated for military application in field trials using internal combustion engines for energy supply
- Advanced telepresence will be essential for remote maintenance of equipment. Significant R&D is ongoing in this area and is likely to yield usable solutions for this application within this time frame.
- Locomotion is a key issue: wheels or tracks are not really suitable in many environments, and legged vehicles currently don't perform very well.
- All the former topics are fundamental preconditions to achieve the goal. However, the possibility of having machines that can be remotely controlled by the operators for heavy and critical tasks is already a great step forward.
- Through-the-rock data communication systems have a physical limit in terms of bandwindth. The will be used for shorter distances, but in the long distances fibre optics is the most adequate (and feasible) solution. Improvements must be made however in practical and maintenance aspects (junctions, connectors, ...)
- General comments applicable to the three questions:
    - The past one to two decades have shown that the important evolutions were not driven by particular needs from industry, government or research, but by mass production for wide spread use (e.g. miniaturisation, etc). Practical examples are advances in virtual reality, from which the main stimulus (and funding) comes from the gaming industry, or for GIS where Google Earth (advertisement driven) is now the bench-mark for all GIS-portal projects. On the hardware part one can cite e.g. the widespread use of microcontrollers in new applications or replacing traditional devices, telecom, etc. Note that almost all of these hardware components are 'modular', meaning that the individual parts are used for very different purposes.
    - Applied to the questions of this survey, this would (and in my opinion does) mean that judging if future achievements are realistic should not in the first place be based on absolute technical difficulty. The risks and magnitude of the effort to develop advanced robotic tools is too large compared to the potential benefits of this ad-hoc goal.
    - The way that these achievements would come within reach, is when profit can be taken from “general purpose” developments, meaning that things would not be designed from scratch, but largely through assembling of parts already available for other purposes. Think along the line of e.g. household robots (for cleaning and other purposes). Widespread use and consequent rapid development will likely lead to more wide application of modified versions of largely autonomous, cheap robots in professional environments such as industry, but also mining.
    - This is what makes the most advanced option (question 3) dramatically less probable than the first two: in contrast to the first two options, I do not see where that kind of technology can be copied from. Too much new elements need to be developed to make this a reality.
- All this improvements or developments appear to be feasible to get, nevertheless robotic companion and wireless super communications through the rock will need more than technological development. I think that these two subjects will need some basic science.
- The vision needs basic research in Engineering Intelligence area, which means that information flows, competence cumulation, collaborative processes and built-in intelligence in machines have to be researched by multidiciplinary research groups. This also needs concurrent development of all these areas. By that way it is possible to develop really intelligent mining technology, where the knowledge acquired is the driving force and the processes are designed so that they are producing context-aware information.

- Materials science is of highest importance to make use of materials that ideally fit the conditions of the mine: the right steels etc. for the given rock characteristics and the "micro climate"
- Most of the envisioned technologies already exist today or are under development. The only exception is long distance communication through hundreds of meters of rock, but such technology might not be needed as there will always be direct connections between the underground workings and surface is which communication devices could be installed. These devices however should be robust and able do rapidly transmit large amount of data.
- To work autonomously and economically effectively, all systems must be extremely robust with exceptional MTBF. Mining methods and mine planning will need to be based around new technologies - hard to adapt existing mines cost effectively.

Selected Comments to Statement 1 - Group B

- I think that for really intelligent machines as the ones requested 2050 is too near.
- I don't believe for one second that human workers wont be found underground. Two reasons: (1) while to robotic aspect will be at the good level, AI still has a long way to go -- as such, robot-assisted human workers appear to be much more realistic (2) unfortunately, the human workforce may still be quite inexpensive. I do believe though in fully autonomous robots for relatively stable tasks, such as on-the-fly building a communication networks or autonomous SLAM in any environment. Then, for difficult tasks, I would guess that AI will be useful enough to assist a human driver, but not replace it in most case.
- Humanoid robots are overrated, specialized machinery is much more likely.
- The key issues are autonomy and adaptivity (of the new kind of machines). These must be targeted in the first place. Exo-skeletons and teleoperation are nice, but do not lay on the critical path to his target.
- Other preconditions: modular and robust design of heavy machines for better maintenance, flexibility or self-repair.
- I think that the mines will be operated primarily by semi-autonomous systems, with occasional human telepresence/exoskeleton assistance. I don't think wifi will ever work through thousands of meters of rock.
- With proper research it should be possible (and preferable) to fully automate this task. Thus human augmentation and telepresence are not required. Companion robots may be an effective method for training, but such robots do not necessarily have to be humanoid.
- Novel brain-inspired computing technologies (e.g. neuromorphic VLSI) are developed that allow machines to interact with the environment in real-time. They will be able to learn about the statistics of the environment, learn about the actions required to accomplish a specified task, carry out state- and context-dependent tasks, and plan and adaptively change plans to achieve their targets, based on the current state of the environmental conditions.
- Given the large and complex structure an underground environment is likely to exhibit, I believe that the use of multiple robots is a necessity. The biggest challenge to realize the described vision is then to coordinate effectively large groups of robots, for which aim today little is readily available. In addition, it is extremely likely that robots specialized for different tasks will be necessary (diggers, extractors, explorers, etc). The complexity of developing autonomous coordination strategies in this scenario vastly exceeds that of developing a single autonomous robot. In my opinion, the most likely achievement by 2050 will be some sort of semi-automatic operation regime in which human supervision is still required.
- Even autonomous solutions are designed, all solutions need human, which makes human factors (human-technology interaction, user factors) crucial.
- An important game-changer would be adaptive systems: systems (robots) that can adapt function and possibly shape to handle the dynamics and risks of working where direct human

control is not feasible. Evolutionary computing, in particular evolutionary robotics research provides promising inroads to tackle this problem.

- Adaptive and self-aware swarm-robotics functioning provides fully autonomous behaviour.
- Swarm robotics characterized by knowledge rich and self-aware behaviour will contribute in providing a highly intelligent and effective tool for heavy and dangerous tasks.
- Robotic general AI is a prerequisite for all of this and not enough companies are doing this at the moment.
- Exo-Skeletons, Wearable robots etc. will be used to spend less time in the preparation stage of the work, i.e. to move faster from place A to place B. But for the real and heavy tasks a swarm of smart robotic companions and smart specialized autonomous machinery will be the best fit for carrying out the various tasks. They need less installation and (permanent) infrastructure costs, are quite flexible and trainable to various tasks. Research in swarm intelligence, deep learning concepts for situation processing (recognition, interpretation, coordinated reaction) to perform the overall task (mapping of the "doing" to the "task description"). With versatile telepresence technology, human teams can monitor, coordinate and control the swarm of machines. Robust wireless communication and sensor technologies are prerequisite to gather and communicate data and control within the human/machine team. Research in environmental sustainability is also a must or prerequisite.
- Waveform propagation has some physical limits. Nevertheless, communication paths form ground down to the mine can be also developed without going through the rock.
- Related research areas that should be supported include Safety-critical Systems, Reconfigurable Computing, and Machine Learning.
- I am doubtful about humanoid workplace assistants being sufficiently well developed, for this kind of advanced task, within this timeframe. Similarly I think fully autonomous systems unlikely. Instead I think wearable, and then tele-operated systems more realistic. Something not mentioned here is swarm systems, i.e. multi-robot teams which are semi-autonomous and either tele-operated or have a human ''team leader'. I think such systems could be very important in future mining.
- Applied Neuroscience and Brain Related Research, including psychological evaluation of workers condition (stress, attention capabilities...) should be considered especially if Human Augmentation solution would be adopted.
- Robotics, communications, visualization, wearable computing, dependable computing
- Communication through rock at high data rates is subject to physical limitations. It is more likely that the machines will become more autonomous and require less communication with a control room.

Statement 2 ***"In suitable formations mining and (pre-)processing is done by small autonomous robots without creating large cavities"***

No of responses Group A: 60
Probability of occurrence by 2050 Group A: 49.3 %
No. of responses Group B: 39
Probability of occurrence by 2050 Group B: 61.5 %

Precondition	Group A		Group B	
	Agree	Disagree	Agree	Disagree
Precondition 1 Novel extraction methods are developed for light machines in order to manage/avoid reaction forces during production	50	10	32	7
Precondition 2 Radically improved power efficiency and energy storage solutions are developed for the autonomous devices	47	12	30	9
Precondition 3 In-situ energy harvesting and flexible distribution of energy is developed (e.g. wireless power)	30	30	29	10
Precondition 4 Self repair and self-healing capabilities are embedded for individual units, advanced service robotics is available on swarm level	30	30	25	14
Precondition 5 Reliable high-bandwidth wireless communication is available with realtime data sharing and collaboration across machinery of different functions, sizes and complexity	50	10	36	3
Precondition 6 Machines must be capable of the autonomous evaluation of the characteristics of the produced rock and able to optimise performance and resource usage in response to changing conditions	47	13	29	10

Selected Comments to Statement 2 – Group A

- Machines able to assess the mineral content in the rock present in deep underground mines
- Here accent must be given to development of machines capable of the autonomous evaluation of the characteristics of particular excavated rocks, which will contribute to performance optimisation
- Autonomous robots will definitely be developed. I can also imagine that those robots will work in swarms. However, the forces and also the reaction forces occurring during mining operations will always remain significant so that concepts nowadays developed for aboveground applications will most likely never be suitable for underground operations. A change in paradigm will be necessary in the development route. Characteristics like robustness of the devices and highest possible energy release as tools for mining operations need to be predominant.
- We don't think this scenario is very likely to happen due to missing self-learning and self-repairing capabilities.

- All these preconditions should be given to reach the goal but we are far to achieve some of them. In 2050 we can reach the developing level for some of them but we need to move faster to the demonstration and higher TRls to see them within the real mines
- Enhanced robustness of machinery will be superior to on-site autonomous service capabilities. Transport of matter is not covered here, but this will be an essential R&D issue.
- I think it is possible but more basis research for in-situ energy harvesting and self-repair is necessary
- Irrespective the fact that very intelligent ICT tools will be developed, geologist (and engineers) are still needed to intervene in all steps of the mining process.
- I believe that the need to increase profitability (by increasing the cut off ratio and improving processing performance) will boost this scenario, that can occur (or start) by a mixed solution, combining areas (galleries) accessible to humans (for maintenance and control purposes) with exploitation galleries, with small cavities only accessible to machines.
- I think the need for small machines depend strongly on type of mineral, are they required in bulk or rather precious materials. For bulk materials this is not needed so much, but I am not an expert in this field.
- “High bandwidth communication”: ants communicate very basic, but are able to do very complex work - so i do not think this is needed…
- Even using artificial neural networking, fuzzy logic and other advance decision making tools requires both very large data base and a very large number of logical statements.
- Further processing such information can not be programmed without prior experience and no amount of simulation can overcome the expertise of human brain specially for rapidly changing conditions in underground such as rock burst, sudden water seepage and discontinuity of ore bodies due to unknown geological conditions.
- This will be available, but not in 2050... more likely in 2100. Too many technological restrictions are still unsolved. A lot of basic research is needed.
- The reaction problem may be important in space, but not in terrestrial underground mines, especially when operating in small cavities - bracing against cavity walls should be sufficient. In-situ energy harvesting is impracticable. However, the use of geothermal energy from temperature difference between surface and underground may allow creation of shaft-bottom battery re-charging points. High-bandwidth communication as described will require careful definition of coms standards, not only at the hardware level but also at the more complex instruction level, so that robots with different complexity levels can communicate effectively. Autonomous evaluation of produced rock will require the same sensor technologies already identified for the previous question - chemical and mineralogical characterisation - plus identification of mechanical properties of the rock to optimise fragmentation. New fragmentation technologies may well be required in addition to, or replacing, mechanical crushing and grinding. Key research fields: sensor technologies, coms standardisation including software standards, energy-efficient fragmentation technologies
- Comments on: *“Monitoring by humans was seen as desirable, but given the extreme conditions strong autonomy of the machinery will be required so that the machines could continue operate in the case of lost communications.”* This would need strong security on failure conditions, that the machinery does not harm each other, continue on wrong direction etc. Control on machinery should not be completely lost.
- It is emphasized that everything has certain limitations. Our knowledge regarding the processes of formation of ore deposits is not full proof. The robots with very high level of auto signalling can be entrusted to such work, only when we are able to establish all the geological conditions, which control the entire morphology of the deposit, even at ultra depth.

- While swarm robots have been demonstrated, they are very basic and have serious issues with power to weight ratio. In this timescale the development of long thin burrowing robots of differing scales that lay communications / power lines as they progress, are likely and overcome challenging power and comms problems.
- "Self repair and self healing - I don't think so, but advanced service robots at swarm level will happen.
- The major precondition is for a novel extraction method, and right now it is difficult to foresee what that might be, but by 2050 we should have cracked the problem. Another important precondition is related to the need of mining extremely hard rock with small machines
- In my opinion, the biggest challenges will be in-situ energy harvesting and self-healing capabilities. Although they are extremely interesting, there are only at the beginning of their research. Hence, it is not clear if the science community will be able to come up with (economically sensible) solution by 2050.
- Most of these statements completely ignore that assessing ore and rock is more of an art than a science. I agree that better and more efficient machinery will become available but not to limit reaction forces but to safe fuel costs. These will be developed mainly for mines outside the EU.
- Power efficiency and energy harvesting are no preconditions for this technology to become reality, nor is there reason to anticipate them. This technology is more challenging to realise, with higher uncertainty that essential obstacles are successfully encountered (e.g. self learning, swarm intelligence/operation), but if realised, extremely important for European context.
- In my opinion the emphasis of these statements is focused in the collaborative issues but not enough in the individual robot capabilities. Those capabilities are going to demand very hard research effort, as for example in the "THE AUTONOMOUS EVALUATION OF THE CHARACTERISTICS OF THE PRODUCED ROCK" statement, this is a very important research line.
- This is a more demanding challenge that previous, but still achievable. This needs research of swarm intelligence and control, but more challenging task might be to develop extraction methods with are small and light, without any big forces....
- Wireless power - unfortunately – will not be possible by 2050
- Autonomous evaluation of the characteristics of the produced rock would also depend on human evaluation, if not even dominantly by human evaluation. Algorithms that consider most geo-technical and technical eventualities sufficiently are difficult to imagine
- Resilient communication technology at various levels (short distance machine - machine, machine - human and long distance front - surface) is paramount to realise this future. Another crucial element is energy. This asks for improvement of energy efficiency of mining devices, improved energy storage options and possible the development of small generation units and efficient charging technologies. A lot of R&D is going on in these fields nowadays, though not related to mining. A transfer of the new techniques to the mining world will be needed. In fact, (surface and in a later stage subsurface) mining could be create unique settings to introduce e.g., high performance battery for electric vehicles or inductive charging stations, as the additional costs for the new technologies will less detrimental for already expensive mining equipment than for consumer products.

Selected Comments to Statement 2 – Group B

- I would say the limit is to be found in the inability to design fully autonomous systems with strong adaptation capability. Helping diagnosis and advanced monitoring may still keep a human in the center of the decision process.

- As for self-repair, it depends on what is implied by this term. OK for limited self-repair, or possibility of the existence of ""robotic repair shop"" where one (moderately) damaged robot can go by itself. However, full self-repair, use of external resource to achieve self-repair, seems a bit too science fiction to me, at least in this context.
- Swarm robotics and evolutionary robotics are existing areas of extremely high relevance to this vision. However, they need to improve/develop significantly in several dimensions, e.g., controllability, scalability, methodology (design, testing, verification). Bio-inspired approaches are very promising, but need to become more practical.
- Small robots? Weird. All these points will be kind of needed. Autonomy energy-wise seems most relevant. Autonomous evaluation seems scifi, a hard AI problem, so the overall goal will not be met.
- Online chemical analysis of environment and of the produced rock in order to increase efficiency. Chemical or better optical sensors required.
- All points above require the pre-condition mentioned for statement 1 on neuromorphic VLSI technologies.
- My comments here are analogous to those I reported in the previous statement. While power efficiency seems to be achievable in a medium term because of the increased international effort in this direction, robot autonomy (both at the individual- and swarm-level) seems to me a much more difficult goal to reach in just a few decades. Most of today's research in artificial intelligence has little applicability to real problems with real hardware. To achieve this goal, a more coordinated effort in both robotics and artificial intelligence research is necessary.
- Works on self-* autonomous behaviour is well advanced, so that the above statements are likely to happen by 2050
- Swarm- and modular robotics provide a natural avenue of research in this area, in particular when combined with nature-inspired techniques such as evolutionary robotics
- Basic research in fields of energy harvesting and energy distribution is still required.
- Wireless power is unlikely as transmission though rock is much harder than through air, energy harvesting must more likely
- Some of the technical requirements are already there; the major shop stopper could be regulations and responsibilities (who is the final responsible for an intelligent equipment in the field; who is to blame/take responsibility?).
- Related research areas: high-performance autonomous systems, self-optimising and self-verifying technologies
- Robust communication and task sharing methods adapting to the environment are needed
- Although I am not a mining engineer, I think all of the above pre-conditions are realisable in the time frame. However, I am doubtful about full autonomy. I think there will need to be human oversight and monitoring - i.e. monitoring of positions and status of the robots, and - at some level - human control. I also think that significant work needs to be done to develop methods for verifying these systems.
- ECONOMICAL FEASIBILITY needs to be monitored. Self Repair and self healing features will be probably not fully ready as well as the underground wireless communication system
- In addition to the domains mentioned previously: energy supply is indeed an important topic here
- These features should be technically possible and available in robust implementations before 2030. The speed of advances will depend on economic necessity.

Statement 3 ***"Deep mines are self-contained ecosystems"***

No of responses Group A: **58**
Probability of occurrence by 2050 Group A: **36 %**
No. of responses Group B: **38**
Probability of occurrence by 2050 Group B: **38.2 %**

Precondition	Group A		Group B	
	Agree	Disagree	Agree	Disagree
Precondition 1 Knowledge to design the mine as a single adaptive system in which a highly heterogeneous set of units (robots, machines, computers, various supporting devices, etc) are interconnected, operating at different temporal and spatial scales, capable of avoiding conflicts from the different objectives and goals of the individual units.	48	10	29	9
Precondition 2 The development of "vital sign" monitoring of such complex artificial systems and the development of new modalities of human perception and understanding of such "vital signs".	36	22	24	14
Precondition 3 The development of fully reliable autonomous machines that are able to evolve, learn and respond continuously to extremely harsh environments and changing operating conditions.	37	21	31	7
Precondition 4 The development of molecular-scale autonomous devices performing simple production and/or processing functions (for example replacing chemicals in leaching production techniques).	26	32	19	19
Precondition 5 The development of novel energy harvesting, distribution and storage methods fully integrated with the minerals production/processing cycle (eliminating downtime due to lack of power).	37	21	26	12
Precondition 6 Embedded self-healing, self-repair functions that work on both overall systems and unit level.	34	24	29	9

Selected Comments to Statement 3 – Group A

- These developments will be more or less possible, only if first the human - computer interface combination is used for mining. This may be possible only depending upon success of an interface system
- I tend to stay with this as a highly fictional scenario. The conditions underground and especially the expected ones in future underground operations will prevent all those highly

complex and sophisticated systems from working properly. A mine is a place where the unforeseen is normal.

- It will be ideal if the extraction could be specifically designed for taking out the mine only the added value materials. This means that we need equipment and machines capable to analyse and decide if the material is good or not. Less human intervention as possible mainly for dangerous activities.
- In my opinion the major weakness of this scenario is to consider the possibility of having robots with self-repair functions (meaning robots that are human maintenance free). If this technology arises it will be at the development level by 2050, and under those circumstances I believe that maintenance needs will be high and very specific, and will involve the need to perform adaptations and improvements that won't be accomplished by self-repair robots.
- Probably this is a requirement more relevant for space exploration and should not yet be a concern for the mining industry now.
- The major problem envisaged at this stage is the option on processing the ore underground and send only the refined minerals to the surface for further extraction vs. the total extraction of metals underground by chemical/electrochemical/biological means that eliminates many environmental problems on surface such as waste disposal and to some extent energy saving.
- Till date only one or two bacterias are capable of metal extracting and a very major breakthrough has to happen for designing metal/s specific bacterias to extract metal in the underground
- Partial implementation may be feasible but fully autonomous self-contained 'ecosystems' are most unlikely. What is likely is the integration into more conventional mining (using semi-autonomous robots etc.) of bacterial processing within ore bodies to extract required minerals in solution or in bacterial biomass. Artificial mechanical/chemical molecular-scale autonomous devices seem less likely to be used, purely on a cost basis.
- 'Vital sign monitoring' is likely to develop in any case even for a more conventional tele-operated mine, where sensor feedback from across the whole mine is managed to give indications of potential problem areas. Self-repair of robots is going to be essential in any mine where human presence is excluded. However, this could be through separate semi-autonomous or tele-operated maintenance-bots.
- I disagree with some of these preconditions because I consider some of them too much technologically advanced for year 2050. I think that the statement that deep mines are self-contained ecosystems is unlikely to occur by 2050.
- Fully self-contained may be too optimistic, but very minimal intervention is more realistic.
- The total integration will be the great challenge of ICT. The technological developments is needed both hard technologies in manufacturing (partially on-site) and material science and in soft technologies (sensing and internet of things). Each operation and each component should sense the environment and should be connected into whole system.
- I stand by my previous comment on the earlier comment on the previous question. Here also I particularly emphasize that the natural phenomena are complex and being controlled by multiple factors. Accordingly, it would be risky to comment that everything is achievable by the humans in future, as there would be further mysteries of the nature to be solved by the human experts.
- Molecular scale autonomous units seem to be still science fiction. So far there does not exist animals/organisms that would process rocks and spit out steel. Then again, this is opinion of a mechanical engineer and not a bio/animal-scientist.
- I think maybe there is also the notion of a micro-mine or structure-less mine. In the sense that a small energy harvesting robot can borrow down and extract resources given enough energy which given the low amounts of energy that can be harvested translates into long

time. These may of course work together to make the operation more fast and efficient. So maybe structure-free multi-robot mining is a useful term.

- If you use the model of 'Mothership' deploying robot children to harvest particular minerals or carry out repair / service functions then these children do not require full autonomy, just intermittent communication with the mother-ship. Likewise the mothership may, through relay beacons have intermittent communication with surface humans. There is a much stronger requirement for very high levels of reliability and redundancy. Self repair is more likely to take the form of replacement of damaged sub-units at the mothership (segments) of a child robot responsible for tunnelling or locomotion by ejecting a damaged segment and docking a replacement segment.
- It is going to be a long time, I think well past 2050, before machines are able to repair machines in a closed system. At least for a good while, repair will be by module replacement, which requires a supply of modules. I don't see biological type self-healing processes by 2050, but then biotech is not my field.
- I'm very skeptical about energy harvesting. Unless the rock itself contains energy (like uranium or coal) then I don't think there is enough energy in the underground environment for it to be harvested. For example, heat energy methods require a heat differential, which isn't available.
- Again, this statement and the corresponding precondition focus too much on the production process. However imho such an 'ecosystem' requires more knowledge on the system itself which only can be acquired by innovative exploration tools and techniques.
- Comparable schemes for deep ocean mining were proposed early 1970'ies, but never became through. Based on this similarity, I'd say the gap between concept and reality is probably wider than it seems, with an under-appreciation of the fundamental problems that need to be dealt with.
- Basic research in the so called geometallurgical area are going to be necessary for this goal, there are lots of research lines related to the mining methods and nothing to do with robotics that are unavoidable background for these statements.
- This needs a lot of basic research and new technologies. The most difficult task is to ensure reliability of the machines. However, if the extracting process can be optimised and simplified, this scenario is possible in a long run.
- The cost-benefit-ration for such enterprises will limit their implementation. These techniques finally compete with submarine mining and extraterrestrial mining. Consequently, the extension of the underground "mining space" might be limited on some few kilometres below the earth surface
- Whether or not such a future might materialise will strongly depend on the development of some kind of artificial intelligence. The single adaptive system - or call it mine brain - should be able to learn and improve itself. This asks for the development of self learning algorithms that have predictive capabilities and self-adaptive hardware. If not, control will remain in the hands of humans.
- Human presence for solving complicated problems will probably be needed in the next few decades but at special geological conditions it can be eliminated.
- Depletion of accessible ore bodies means that ever more extreme environments need to be exploited - deeper (hotter) and sub-sea. Full autonomy probably not the first step: development of existing automine human controlled systems would seem logical pending reliable development of artificial intelligence.

Selected Comments to Statement 3 – Group B

- I think that for really intelligent machines as the ones requested 2050 is too near.
- Here, also, basic research is required for self-healing and molecular-scale devices

- Multiple challenges remain to be solved, and 2050 would be a date where I envision that research will have grasped important key issues, but with application still 20-30 years away. Basic research areas required for this would be inbetween optimization and evolutionary ecology -- to understand biological mechanisms in such a way that makes it possible to be reimplemented and torn to our own objectives. Also, the hardware is yet to be designed -- IMHO, existing hardware is no way near such objective.
- This is right in the middle of my vision on future evolutionary robotics. See http://www.cs.vu.nl/~gusz/papers/2012-EVIN-Embodied-Artificial-Evolution.pdf The really essential parts here are the lifelike properties, evolution (needs self-reproduction), learning, self-healing/repair.
- I disagree with all the self-* buzzwords, because they do not say anything and are not realistic. So, who knows if we need them...
- Not sure that molecular scale devices are required, although this is an interesting idea. Energy harvesting may be a feasible approach.
- This vision seems to me completely unattainable by 2050. All of the above statements require decades of basic research.
- Self- and autonomous behaviour research is already looking at some of these statements (even though not in mining conditions)
- Evolutionary, modular and swarm robotics, reinforcement learning and artificial immune systems
- General purpose system integration means (interfaces, protocols, etc.) in presence of self* (features) still needs to be researched.
- Most of the technology is in place. However, what exactly is self healing from a SW perspective can be VERY different in a mechanical environment. Energy harvesting in a mine can be a major challenge.
- Self healing and repair are crucial to this
- Should develop large-scale simulation capabilities to explore scenarios related to this statement; also need new theory and practice of self-contained eco-systems and their application to mining.
- Self repair at unit level needs much more basic research
- Although I think the preconditions here are very difficult to achieve, all are possible with the right effort and investment. But I think the likelihood of such systems in use by 2050 rather low - although demonstrator systems are possible. One of the most interesting area is self-evolving systems which are - I think - feasible and interesting for this kind of scenario.
- I am not sure about a fully autonomous system that digs and maintains deep mines without human intervention, however to a certain degree, autonomy should be included to operate efficiently, monitored by the human.
- Develop new reasoning capabilities for problem solving

5. Evaluation

Experts contributing to the Delphi survey were predominantly male (82%) coming from the Academics (51%) with a strong background in geological engineering (56% of the respondents marked 7 or higher on the expertise indicator). Other significant sectoral representation was Government/Public body (18%) and Industry (11%).

Gender	Age	Sector	Raw Materials	Mining engineering	Geological engineering	Mining ICT	ICT (general)
male	55	Academy	7	10	5	10	9
female	46	Academy	1	2	1	5	8

male	60	Academy	3	3	9	2	1
male	38	Academy	7	3	7	2	2
male	57	Academy	9	3	9	2	5
male	59	Academy	8	6	5	5	3
male	49	Academic	8	2	4	6	6
male	43	Academy	3	3	3	3	7
male	65	Academy	8	1	10	3	1
male	63	Specified: Geological survey	10	5	10	5	6
male	37	Specified: raw materials	9	7	9	7	6
male	65	Specified: Consultant	9	4	3	3	2
male	46	Industry	8	6	5	5	4
male	43	Academy	8	3	10	6	6
male	53	Public/Government	10	4	9	1	1
male	66	Industry	6	4	10	10	7
male	47	Academy	4	5	10	7	9
male	55	Industry	9	3	9	3	5
male	35	Academy	9	5	9	3	2
male	51	Public/Government	7	2	8	3	3
male	56	Academy	5	6	6	6	5
male	34	Industry	8	4	4	6	6
male	46	Academy	8	1	10	3	1
female	39	Public/Government	7	7	2	2	2
male	50	Academy	5	7	4	7	7
female	45	Academy	10	8	7	6	5
female	34	Specified: Industry Association	7	1	1	1	1
male	65	Specified: field geophysicist consulting	8	7	8	7	7
male	53	Industry	8	3	9	4	3
male	39	Public/Government	2	4	8	4	3
male	52	Industry	8	10	8	10	9
male	40	Public/Government	8	6	9	6	7
male	57	Academy	10	2	10	3	3
male	47	Specified: European Federation of Geologists	8	7	8	8	6
female	39	Public/Government	2	1	9	1	3
female	47	Academy	7	3	10	1	1
male	29	Public/Government	1	1	1	1	2
female	36	Public/Government	8	4	8	4	7
female	48	Public/Government	9	2	8	5	5
female	35	Academy	2	5	3	10	10
male	36	Specified: research	8	6	9	5	7
male	43	Public/Government	8	6	9	5	6
male	44	Public/Government	7	7	8	7	7

male	53	Academy	8	10	4	8	2
male	41	Academy	2	3	2	8	8
male	36	Academy	10	6	9	4	3
female	61	Academy	8	2	9	2	1
male	59	Specified: Consulting and Industry	10	8	5	7	4
male	58	Specified: consultancy	8	3	9	3	2
male	63	Academy	2	8	2	6	3
male	43	Specified: industrial research institute	8	4	9	2	1
male	63	Academy	9	9	9	6	6
male	66	Specified: Retired academic	4	6	10	5	5
male	50	Specified: Non-profit research organization	1	3	3	4	6
male	35	Academy	2	9	7	9	9
male	48	Academy	5	4	6	4	4
female	39	Public/Government	5	5	5	4	4
male	72	Public/Government	10	8	9	8	6
male	58	Academy	10	9	8	9	9
male	50	Industry	7	9	5	7	2
male	45	Academy	1	1	1	2	10
male	38	Academy	2	2	2	2	6
male	28	Academy	2	2	2	6	9
male	51	Academy	5	9	5	5	3
female	38	Research	2	1	8	2	2
male	34	Academy	8	7	10	7	7
male	49	Academy	7	9	5	7	5
male	31	Academy	4	6	3	8	9
male	60	Specified: Educational-Research Institute	1	1	5	1	10
female	55	Academy	7	10	9	7	3
male	50	Academy	1	1	1	1	10
male	47	Academy	1	1	1	1	8
male	60	Academy	7	5	9	3	3
male	49	Academy	6	5	6	5	5

Very few experts claimed high level of expertise in more than 2 categories, which resulted in a "mean expertise" for the group to be in the overall range of 5-6. Altogether the composition of the group was well-balanced, cutting through a range of relevant earth-science professions:

Expert background	Self-assessment of expertise
Raw materials	6,2
Mining engineering	4,8
Geological engineering	6,5
Mining ICT	4,8
ICT	4,9

In addition to the above fixed categories experts had the opportunity to create their own category and corresponding marks. These "own-defined" expert backgrounds were also highly relevant for the project, below is a list of records scoring 9 or higher:

Expert background	Self-assessment of expertise
Industrial engineering	10
Materials in product design	10
Mechanical and mechatronics engineering	10
Geometallurgy	10
Mineral Processing	10
Electronics/Instrumentation	10
Work environment	10
Geological mapping	10
Project Management - extractive industries	10
Environmental sciences	10
Extractive Metallurgy and Mineral Processing	9
Mining economics	9
Field exploration	9
Management	9
Energy	9
Computer & Machine Vision	9
Environmental Management	9
Social impacts of mining	9
Robotics	9
Construction Engineering & Management	9

Altogether 74 experts participated in Round 1 of the Delphi and 63 in Round 2 representing 29 countries. The mean age was just below 50 years, indicating predominantly "senior" expertise (Figure 1).

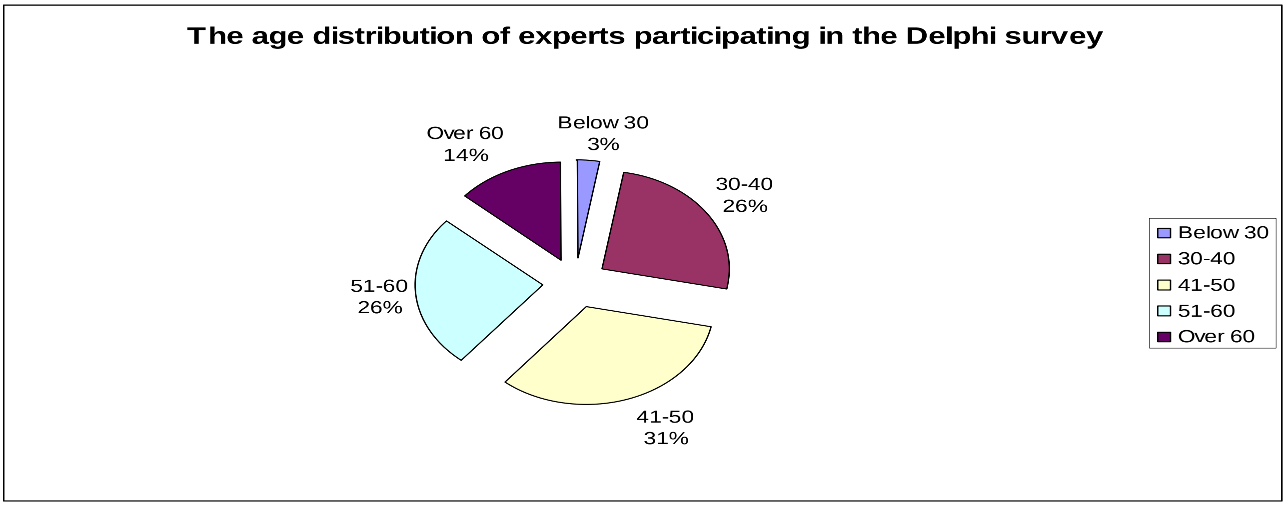

Figure 1. The age distribution of experts in the Delphi survey

Experts from the following countries contributed to the survey:

Country	Number of participants
Germany	10
Belgium	5
Finland	5
Hungary	5
Italy	5
Australia	4
UK	4
Greece	3
India	3
Spain	3
Sweden	3
US	2
Austria	2
Croatia	2
Portugal	2
Romania	2
Turkey	1
Albania	1
Bulgaria	1
Canada	1
Chile	1
Czech republic	1
Estonia	1
France	1
Macedonia (FYROM)	1
Poland	1
Russia	1
Singapore	1
Slovenia	1
South Africa	1

Countries with a strong mining industry and/or historical mining activities were strong contributors in numbers (Figure 2: 3 or more experts from the same country).

Delphi Round I top responders (3 or more from the same country)

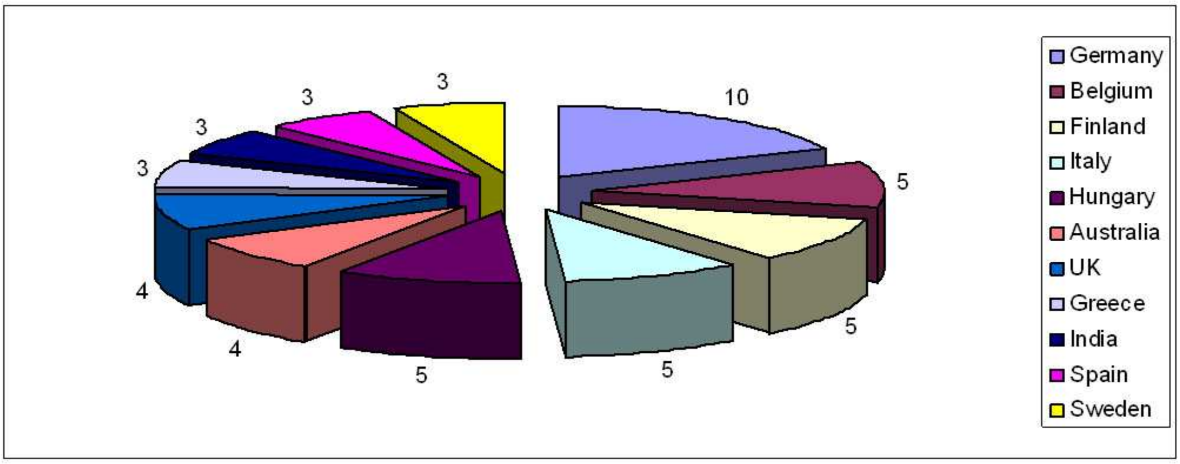

Figure 2. Expert participation in Delphi Round 1

Since the original Delphi was directed towards the earth science community an additional survey was later arranged addressing explicitly the FET ICT community. This survey provided additional records by 47 experts. Altogether 121 (110) experts were mobilised with the help of the two surveys.

The additional 47 experts representing the FET ICT community gave their view in a separate survey which was identical in content to Delphi Round 2 but responses were saved into a separate database. Statistical information on this group was not collected, but predominantly they are of academic/research background, and they were contacted due to their leading roles in completed/running FET ICT projects.

Round 1 results

For the first round of the Delphi survey respondents were asked to choose between two different Futures and formulate their responses according to the selected Future when filling in the survey. This method worked out very well, only one negative feedback was received by a prospective participant, who claimed that he could not identify with either Futures, and decided not to participate in the survey. 65% of the experts selected Prosperous Europe and 35% selected Fragmented Europe (see Annex for details). Experts coming from EU countries with a strong economy tended towards selecting Prosperous Europe (for example all contributing experts from Germany and Sweden selected this Future).

Statements' overview:

- **Statement #1** *„Dangerous and heavy tasks are no longer performed by humans underground"* was a cross-cutting statement and the most successful in generating comments. The overall feedback in both groups was that such development is likely to be realised on a short timeframe. In the Prosperous Europe group 49% of the respondents envisioned such development by 2030. The Fragmented Europe group was somewhat more conservative, especially on a conceptual level ("*some underground tasks will always be dangerous"*) and 15% of the respondents answered that such development will never be realised.
- **Statement #2** *„Virtual support staff in augmented reality is available in deep mines"* responses by experts in both groups were similar especially with regards to the type of research required (predominantly applied research). Several comments to this Statement identified an important precondition (further development in broadband communications and wireless technologies). The general impression was that VR technologies are already mature and their development is likely to be driven further by other industries (e.g. gaming).
- **Statement #3** *„In suitable formations mining is done by small autonomous robots without creating large cavities"* was also commented extensively in both Futures. Mining engineering comments revolved around the need for novel excavation methods (given as a strong precondition) and the need for energy distribution/energy storage solutions. Several comments addressed the need to develop novel sensor technologies, increasing autonomy, increasing the reliability of communications and the need for further advances in swarm robotics (basic research topics). Experts in both groups agreed that in addition to applied research substantial basic research is also required to make this Statement come about. The technological challenges were seen as high or very high (over 70% in both groups).
- **Statement #4** *„Autonomous, ICT-controlled bio-mining is a leading production method"* raised several questions/comments related to environmental security in both groups. Also,

many experts were not familiar with bio-leaching technologies, which is a rather specialised field within minerals processing. For this reason some experts did not provide comments that could be substantiated. The overall impression in both groups was that basic research (35/36%) is required for this Statement to be realised. In addition 20/27% of the respondents believed that such technology will never occur.

- **Statement #5** *„Collaborative robots in-situ process ore deposits"* In situ ore processing was seen in both groups as a key requirement for environmentally friendly future mining. Comments by experts with a mining engineering background connected this statement to the previous one (i.e. mineral extraction and mineral processing should be done as an integrated process). The volume increase of excavated materials was noted several times as a general obstacle to "zero-waste mining". Experts with a strong ICT background often commented on the need of collaboration, communication and task sharing between the units as well as the need to develop novel sensors. Realisation date was perceived very similar in both groups and high/very high technological challenges corresponding to such development.
- **Statement #6** *„Deep mines can be controlled and operated from anywhere"* was seen in both groups as a technology that may be realised in a short timeframe (52% in Prosperous Europe and 50% in Fragmented Europe foresees realisation by 2030). Several experts felt that this could already be done today. Communication and VR/enhanced telepresence were mentioned as important preconditions, but in general very few preconditions/issues were identified with relevance for FET research.
- **Statement #7PE** *„Self-repairing robots reduce downtime"* (Prosperous Europe only) was seen as a Statement with very high technological challenges (52%) and realisable only on a longer timescale (2040 or beyond). The technological challenges were seen as high and developments in other scientific/technological areas (such as materials science) was mentioned as an important precondition. Several experts pointed out under this statement (but also under previous Statements) that (partial) self-repair (or rather "self-healing") could be an important pre-condition for full autonomy in future ultra-deep mines.
- **Statement #8PE** *„Deep mines are self-contained ecosystems operated by autonomous, self-replicating robots"* (Prosperous Europe only) greatly divided the experts. Many considered this statement as the "*ultimate vision*", for others it sounded like "*science-fiction*". Technological challenges were considered very high (77%) and 28% of the respondents marked that such development will never occur. The overall impression (as underlined by comments) is that the term "self-replication" created the greatest resistance towards this vision.
- **Statement #7FE** *„Military and mining research on robotics is performed in the same research centres"* (Fragmented Europe only) The concept was rejected by 40% of the experts (e.g. *"Hardening of robotics is a requirement common to both military and mining applications. However, the sort of hardening required is different for the two"*) but at the same time 17% believed that this is already an ongoing development. The Statement generated some comments related to ethics, security and IPR but did not return substantial comments on ICT.
- **Statement 8#FE** (Fragmented Europe only) *„Disabled people, senior citizens and teenagers are routinely employed by mining companies (via novel tele-working solutions)"* (Fragmented Europe only) was seen as a likely development for senior citizens (not for teenagers) offering research topics primarily with a social dimension: *"disabled and senior citizens /especially those who formerly worked in the industry/ will become an important part of the workforce"*.

Besides a limited number of sociology-related research issues the Statement did not return substantial comments on ICT.

The overall impression is that several statements returned relevant comments and new perspectives, many of them highly relevant for future ICT. Some statements were only superficial i.e. the experts wished to move on quickly to the next statement without further elaboration on their opinion. A single comment has been noted that the survey was not particularly useful, due to the long timeframe is addressed *("I think this survey is not very useful as the alternatives given lie too far into the future.")*. This reveals that, perhaps, further efforts would be needed in the explanation of the specific objectives of such survey, especially concerning FET objectives (basic/exploratory research). The overall "FET-concept" i.e. exploratory, pathfinding, risk-taking research might need further explanation, so that such longer-term perspectives would not be seen "fictional" against the backdrop of the typical applied research objectives.

Round 2 results

Delphi Round 1 results were evaluated and discussed in detail at the Brussels Workshop (12-13 June 2013). A key task for this workshop was also to rule out issues that i) were already being addressed by applied research activities or ii) were considered far too hypothetical (likely not happen at all). These inputs were then used to formulate pre-conditions for the second round of the Delphi. Discussions considered different speed and rates of technology transformation, and eventually three main "scenarios" could be differentiated corresponding to expert expectations for the defined timeframe (2050). Accordingly the structure of the survey was also changed, with focus on technological pre-conditions that would be necessary for the achievement of the "technological scenarios" defined as Statements.

A particular feature of Round 2 implementation is that a separate – but identical – survey was also implemented polling a new focus group (comprising exclusively of FET ICT experts). Experts in this new group had not participated in the previous round of the survey, which allows a comparison between the two Groups beyond the usual Delphi analysis between the different Rounds.

- **Statement #1** (corresponding to Statement 1 in Round 1) was kept for Round 2 due to its cross-cutting nature, proven potential to generate comments and ideas, and also to offer an acceptable "scenario" for some of the more conservative respondents. Economics constituted a significant barrier and it was mentioned repeatedly amongst those, who believed that such development was unlikely (marking between 0-20% probability of occurrence) *"Various countries may have various levels of utilizing the new technology. The big issue is if the new machinery is more cost-effective than human miners." "I believe in increasing of robotization and automatization in mining, but the economical aspects might be really in contrary to such development."* Or simply *"it has to be economical", "economics"*, etc. The overall impression was, however, that this is a likely development by 2050 (64% of respondents). By comparison Round 1 responses were somewhat more "optimistic": 75% and 73% of the respondents indicated that this Statement would be realised already by 2040 - in Prosperous Europe and Fragmented Europe respectively. This could be compared to the responses by the "new" FET ICT group (Group B), where the probability of occurrence (71%) was similar to the Delphi Round 1 responses.
- **Statement #2** (corresponding to Statement 3 in Round 1) shows a similar trend in Round 2 experts being more careful and "conservative" compared to first round responses. The likely realisation dates of Round 1 (58% in Prosperous Europe and 72% in Fragmented Europe already by 2040) have dropped just below 50% by 2050 in Round 2. Group B experts (FET ICT

group) were significantly more "optimistic" (62% probability of occurrence was foreseen by 2050) - but again they were not influenced by Round 1 comments, which highlighted a broad range of relevant technological challenges. Wireless communication for data sharing, autonomous evaluation of mineral characteristics and novel extraction methods were seen as key preconditions that have also received some really high quality comments and ideas in this round. The energy preconditions greatly divided the experts, with the decisive majority agreeing on this being a key issue (several comments as well) but the actual technological solutions (e.g. energy storage vs energy harvesting) represented a clear division line between expert opinions.

- **Statement #3** (corresponding to Statement 8PE in Round 1) yielded similar results in the Delphi Round 2 Group and the FET ICT Group (36% and 38% probability of occurrence by 2050 respectively). One notable difference compared to Round 1 is the overall quality of the comments, which have substantially improved. This could be due to the fact that in Round 1 this Statement was found only in the group that selected "Prosperous Europe", so that in fact the statement was "new" to several experts (those, who selected Fragmented Europe before). Some experts felt that although such developments are not unlikely, the timeframe is perhaps too short *"2050 would be a date where I envision that research will have grasped important key issues, but with application still 20-30 years away"*. At the same time this statement received some of the most elaborate comments and several experts felt that the vision and the topic was highly relevant for FET – *"this is right in the middle of my vision on future evolutionary robotics"*. In fact the preconditions corresponding to the development of evolutionary robotics was very strongly supported by the ICT group (over 80% mentioning *"the development of fully reliable autonomous machines that are able to evolve, learn and respond"* a key pre-condition for this scenario to be realised by 2050).

The overall impression is that Round 2 was characterised by more conservative responses as to the likely realisation date, which indicates that comments from Round 1 have been read and that the experts were willing to re-consider their earlier responses. Statement #3 is an exception, but in this case the Statement has been substantially changed (the term self-replication was removed). The responses by Group B (FET ICT experts, who gave their views based on Round 1 summaries only, and who had not been involved in the previous round) show a more optimistic attitude towards the same topics (Statement 1 and 2). The third Statement yielded very similar results in terms of probability of occurrence (36 vs 38.2 in both groups) with a greater variation in terms of preconditions, where the earth science community shares a similar vision (i.e. geologists' knowledge cannot be replaced by ICT) and the FET ICT community strongly supporting the idea of the development of machinery *"that are able to evolve, learn and respond continuously to extremely harsh environments and changing operating conditions."*

Altogether none of the Statements were considered too hypothetical, which makes the raised concepts suitable for further discussions under a risk-taking pathfinder programme like FET. Although there are signs of converging opinions a third (and possibly fourth) round would be needed to reach a good level of consensus (if this is possible at all) as to key aspects of future underground mining and emerging ICT. Such detailed investigation is out of the project's scope. On the other hand the key objective of the Delphi has been fully achieved: the comments and ideas collected with the help of the survey provide an excellent background for discussions for the conversion of ideas into Call Topics at the final Workshop in Puntagorda, Spain. These comments and future "visions" are based on independent external expert input, moderated by consortium members and as such, they essentially remained unbiased. Evolutionary underground robotics, applied biomimetic artefacts, the concept of a living and evolving mine, molecular-scale ICT devices for minerals processing, in-situ energy harvesting are just a few notable examples of future technological visions, identified by the Delphi expert community that were not even foreseen in the original project proposal.

The overall objective of the Delphi was to „poll" the greater scientific community and collect structured opinions from those, who could not participate in the project workshops. This way it was possible to increase the number of involved experts, who directly participated in project activities. The survey itself has had an important multidisciplinary "community building" role as well, as expressed by the numerous supporting e-mails received by the organisers during the implementation of the survey. FET ICT experts often commented that the survey revealed a new potential future application area for their research. The conclusion is that the Delphi has turned out to be a successful tool in facilitating discussions, sharing of opinions, and, consequently "generating" comments and ideas for further processing.

The Delphi survey represents an intermediate part of the EXTRACT-IT investigation and therefore this study offers only interim results as well. The Final Workshop in Puntagorda, Spain, which will further evaluate results of Delphi Round 2, could produce new insights, which may result in an update of this report. Such updates will then be made available for download from www.extract-it.eu. For further details on how the comments were used in the development of Call topics please refer the Final Project Report and D2.3 Report on the Foresight Exercise. These concluding studies will be presented at the end of the project.

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Annexes