Handbook of Research on Industrial Advancement in Scientific Knowledge

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Chapter 12

To Mine or Not to Mine?
Using Game Theory to Explain the Decision-Making Process in Asteroid Mining Investigations

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ABSTRACT

Social studies of science have flourished within the last decades, making use of numerous intellectual tools from a high variety of academic fields in the social sciences and the humanities (sociology, anthropology, cultural studies, etc.). Game theory, however, has been one tool that has not been put to use too often, in spite of the obvious importance of strategic considerations in the negotiations between the relevant actors in research episodes. In this chapter, the authors illustrate the use of game-theoretical concepts and techniques with the analysis of a nascent research field: asteroid mining.

INTRODUCTION

Knowledge, and in particular scientific and technological knowledge, is usually the product of a complex social network in which innumerable agents interact. Even the lonely inventor or discoverer applies in her discoveries numerous items of knowledge she has acquired in the past through social interactions. The social study of science is a mature academic field since at least the mid 20th century, and has been approached from almost all branches of the social science: sociology, anthropology, political science, and obviously, economics. However, there has been a not easily understandable reluctance by part of most researchers in those areas to apply what some scholars consider to be the most nuclear intellectual tool in the social sciences: game theory (e.g., Gintis, 2009). As one of us has commented in other papers (Zamora Bonilla, 2006, 2007), this neglect has been particularly regrettable in the case of the constructivist sociologists of scientific knowledge, for, though the interests of the scientists and other social
agents (and, in the case of authors like Bruno Latour, the ‘interests’ of the rest of other relevant things, which he calls ‘actants’) are considered by these authors as one of the major explanatory factors of the social situations they try to illuminate, they hardly take into account the problems and the possibilities associated to the strategic decisions that arise once we have more than one interacting agent, in particular the existence of several possible outcomes, not all of them being equally efficient for the agents, nor all of them equally constituting a possible equilibrium in the game that those strategies create. In particular, game theory allows to understand in an easy way some ‘constructivist’ conclusions that have created too much confusion and polemic in the last decades; for example, it gives a clear meaning to the notion that the epistemic value of the products of a research process may not be optimal, but showing that this does not amount to something as a complete rejection of the ‘objectivity of science’, for it simply means that getting an epistemically better output would have had some ‘costs’ for some agents that have preferred not to incur in them, if they have had the chance, but it does not entail that the output has no epistemic value (only that it does not have the possible maximum value... which is compatible with having a very high value). As the product of a ‘social construction’, scientific and technological knowledge has simply the quality level that the combination of the interests and possibilities of the engaged agents have allowed; being a ‘social construction’, hence, does not entail that, for example, a scientific theory is not a good theory as an item of knowledge, exactly in the same way as being a ‘social construction’ does not entail that a hospital is a bad hospital.

In this paper, we want to illustrate the capacity of game theory to make us understand in an interesting way the social processes of interaction that underlie the production of techno-scientific knowledge, by applying game-theoretical tools to a particular example. We don’t pretend to develop something like a full-grown theory about the ‘social construction of science’, but just to offer an impression of how the application of these formal tools might look like. Of course, it is possible to apply them to other, very different aspects of research processes than those chosen by us. The essential thing to take into account is that, in order to understand a research episode from the point of view of game theory, we need to conceptualise it according to the following list of items:

- What are the (most relevant) agents (or ‘players’) involved in the episode.
- What are the actions, decisions, or strategies open to each agent.
- What are the results to which each combination of a strategy for each agent lead to, and how does each agent evaluate those results according to her own ranking of preferences (or, in the language of game-theory, her payoffs). The union of these three elements constitute the description of ‘a game’.
- Taking the former into account, what combinations of strategies can be considered as reasonable outcomes by constituting an equilibrium of the game (basically, what economists call a ‘Nash equilibrium’, i.e., a combination of strategies such that no agent would prefer to choose another strategy, given what strategies have been chosen by the other agents). If the combination of strategies actually chosen by the real agents does not coincide with any of the ones the game-theoretic analysis has tagged, we should either revise our description of the game, or investigate if some non-rational factors have been operating (e.g., limitations to the information managed by the agents, or limitations to their rationality).
- Lastly, what are the normative properties of the outcomes: how ‘good’ are they from the agents’ point of view, or from the point of view of other relevant actors.
In the following pages, we shall apply this framework to the understanding of a particularly significant aspect of the creation of scientific and technological knowledge, namely, the very moment of constituting a new field of research, and we shall do it through analysing a case that is occurring right now: the nascence of ‘asteroid mining’.

**ASTEROIDS MINING**

A particularly fascinating case of intersection between science and technology researches is certainly represented by the space exploration: the primordial attraction that we feel for the stars as human beings, the desire to understand where Life comes from and the aspiration to unlock the mystery of the universe, connect in the space sector with the state-of-the-art technology in a stunning attempt to push humanity beyond its limits, in terms of both knowledge and exploration capability.

And, in the space exploration domain, there is a very young area of investigation where this synergy between science and technology is especially coupled: the asteroids mining. Yes, “asteroids” and “mining”, all in one sentence: something that immediately insinuates in our thoughts a science fiction aroma and that whispers to our mind images from books and movies. But this is not just science fiction: since February 2016, when Luxembourg government announced the intention to create a legal framework to define rights and responsibilities in the industrial mining of small celestial bodies, enthusiasm and scepticism have gone along together in the space sector (see JL Galache, 2016). The satisfaction for the money injection from international investment funds has lived together with the perplexity of those who, better than anyone else, are well aware of the technological and scientific challenge hidden behind the asteroid mining initiative. At the moment when this text is being written there are two US companies leading this new “Space Gold Rush” (Planetary Resources and Deep Space Industries) and the interest in their endeavour has done nothing yet but growing.

But, beyond the fascination and its dreams generating capability, does this initiative make sense at all at technical and financial level? The answer, of course, is not unanimous and we are certainly not talking about something that will concretize in the next few years. But the high money is raising its credibility, always keeping in mind that the next decade (at least) will be dedicated to fill the knowledge and technological gap that made the idea of mine an asteroid just impossible till yesterday. Let’s see some figures.

The number of discovered asteroids has experienced an impressive increase since the start of 21st century: in Figure 1 it can be observed how the amount of known objects close to Earth (NEAs, Near Earth Asteroids), the most interesting ones from the mining perspective, has been multiplied by ten only since year 2000. So we can say that there are out there a sufficient number of potential targets.

Could then these asteroids be profitable? It depends of course on their composition (see De Meo et al., 2015 and Rivkin et al., 2014) and on the physical possibility to extract valuable materials from them (see Michel and Delbo, 2016 and Murdoch, 2016). Let’s say from the very beginning that the main idea is not to bring those materials to Earth, because, except maybe for a utopic golden asteroid, there is no business case for that: it would be too expensive. The plan is rather to exploit the extracted materials directly in space, to build new infrastructure or to store all kind of useful resources such as oxygen, hydrogen, water etc. for the future exploration missions. Due to their weight, in fact, the cost to take these materials into space (i.e. to a Low Earth Orbit, abbreviate LEO) is extremely high, and then the possibility to have them already available in space could be highly lucrative. In the example illustrated in Figure 2, the profitability of a 50m asteroid is detailed, summing up 363B$ (yes, billions!) just as
saving in the transportation cost, so without considering the materials purchase in itself; these values are for a typical 50m, water-rich, C-type asteroid, as inferred from meteorite samples.

Of course this figure depends very much on the asteroid composition, which should be known in advance with a minimum level of detail, and it shall then be contrasted with the extraction cost. And here is where the chickens are coming to the roost: performing space mining means to carry out a space mission, and, whether it is a human or a robotic mission, not a standard one. At the moment this is extremely expensive because asteroids are not easy targets at all, as it is demonstrated by the fact that very few missions have been expressly dedicated to their exploration: NEAR Shoemaker (NASA, 2001), Hayabusa (JAXA, 2005) and Dawn (NASA, 2007 still ongoing). Asteroids are small bodies very far away from Earth: the high cost of reaching them is then combined with the complexity to orbit a spacecraft around them (see Vetrisano et al. 2016), due to the low and uncertain gravity attraction that they exert. If you add to that the fact that they could be rotating in a fast and/or uncontrolled way, it’s easy to understand how hard is the technological challenge to manipulate an asteroid to mine it.

Different challenges are envisaged at technological level to realize the so called “In-Situ Resources Utilisation” (ISRU) with an asteroid:
1. **Asteroids Manipulation:** The asteroid needs to be somehow manipulated to expose the material of interest. This could happen touching the asteroid or also contactless, depending on the extraction technique: the satellite could try to land on the asteroid, to grasp it with some mechanism, to impact it with a projectile or to heat it up to sublimate the contained water and break it up.

2. **Resources Extraction:** Several techniques envisaged for planetary ISRU are presented in literature to extract materials with the limited capabilities of space systems: carbothermic reduction (see Gustafson et al., 2010), reduction by hydrogen (see Linne et al., 2012), Molten regolith electrolysis (see Sibille et al., 2012).

3. **Handling:** Once the material is extracted, specific technologies are required to engage the material and start its processing, going from drilling to excavation, from transporting to conveying and sorting of the resource.

4. **Storage:** Finally, since it’s highly possible that the extracted materials will not be used immediately, they will have to be stored without altering their properties for a potential long time in the hostile conditions of space environment.

Summarising, we can say that several challenges shall be faced to make asteroids mining feasible, challenges for both science and technology: the difficulty and the high cost of reaching an asteroid push toward a very careful selection of the candidate targets, and this shall rely on a robust scientific knowledge of what is being targeted. Then the approaching phase is not trivial at all, nor is the prospecting or the mining stage: dealing with an unresponsive object in a very low gravity environment definitely brings high uncertainties in the mission design and challenge our state-of-the-art technology and knowledge (see Centuori et al. 2016). And the answer to these challenges is not just on technology or science plate, but it is necessarily on both of them.
As an attempt to provide responses to the asteroids miner’s needs and questions, the ASIME (“Asteroid Science Intersections with In-Space Mine Engineering”) conference has been organized in September 2016. ASIME has been conceived as a “focused two-day workshop of roughly 30 scientists and engineers seeks to provide an environment for the detailed discussion of specific properties of asteroids with the engineering needs of space missions with in-space asteroid utilization”. The objectives of the workshop were to place scientific constraints about particular asteroid properties such as porosity, density, chemical elements, and volatile abundance as a function of asteroid type and further about specific asteroids. Moreover the conferences wanted to facilitate new collaborations and partnerships between the research and industry domains. The outcome of the conference has been summarised in the “ASIME 2016 White Paper: In-Space Utilisation of Asteroids: Answers to Questions from the Asteroid Miners“.

Within the scope of the current publication, ASIME 2016 is then selected as a paradigmatic case of interaction between science and technology investigations, especially interesting due to the high innovation content intrinsically associated to the asteroids mining initiative. The framework of this conference is what we are going to take as the stage on which our game-theoretic reconstruction will be set.

THE GAME

The Players

Different players took part to ASIME conference with very different backgrounds, roles and objectives between them. Certainly with a certain degree of simplification, we can divide them into four different categories, which represent the typical high level players of a science-technology game:

- Science
- Industry
- Government
- Public opinion

Of course the boundaries between the different categories are sometime fuzzy and each category encloses a full world inside it; but moving into a more detail description of each of them we hope to provide a solid justification of this choice and to depict with more accuracy the game we dealing with.

Scientists

The scientists who participated in ASIME have very different backgrounds: participating in the conference meant the privilege to listen to talks given by the world top level planetary scientists, geologists and astronomers, like JL Galache, Simon Green, Marco Delbó, Naomi Murdoch, Patrick Michel or Andy Rivkin, just to mention the keynote speakers. Nevertheless we can say, as a general statement and as a first approach to the problem description, that several commonalities can be found in their objectives and strategies; because of that they can be grouped under the same category and then be described as a single player: the “Science” player that will be abbreviated in our graphical representation as $(S)$.
A more detailed analysis would be certainly worth it to grasp all the behavioural nuances associated with the different backgrounds and the various areas of research of each of the scientist taking part in ASIME. However this would complicate too much this first analysis and it is then left as a suggestion for the future works on the subject.

**Industry**

As usually happens to engineers with respect to researchers, industry representatives who participated in ASIME were much less diverse than their scientists colleagues. However a significant line can be drawn dividing them in two groups: space miners on one side, and traditional space industry on the other. The distinction comes from the fact that they share the same objectives, which is true, but with different preferences and employing then different strategies:

- What we decided to call here “traditional space industry”, and which will be abbreviated in the graphical representation as \( (I) \), is represented by very well-established companies in the space sector, companies that have a consolidated track of project in the sector and with short term margin objectives. Smaller industries (like, for example, Qinetiq, SSTL, DEIMOS Space) and large space integrators of satellites (i.e. Airbus, Thales, OHB) belong together to this category: they could look very diverse, but we will see that their behaviour in this context allows describing them as a single player. An important remark is that the companies within this group participating to ASIME were all European firms.

- On the contrary, the “space miners” are very new companies with powerful investors behind them and which aim to develop a fully new technology to exploit the economic benefit of mining asteroids. Their objectives and strategies will then be very different from the other industries: instead of struggling for contracts and customers, their principal goal is to build up credibility to their investors by establishing a solid knowledge basis of asteroids exploitation and by developing the technologies needed to achieve this ambitious goal in a reasonable timeframe. It is proposed then to treat them as an additional and independent player, abbreviated in the graphical representation as \( (M) \).

**Government**

The public sector also plays a critical role in this new research and technology field. It takes part to the game both through national representatives (i.e. the ministry of technology of Luxembourg) and through supranational actors such as space agencies (i.e. the European Space Agency) or the EU institutions (i.e. the European Commission). If we compare their behaviour we can say that they all share the same objectives and strategies, that is to finance basic research and industrial studies and development to foster a technological leadership in what is considered a strategical sector. Nevertheless they of course act at different geographical levels depending on their constitution.

In a first iteration of this analysis it is proposed to consider them as a single player, that rather than a real competitive player is a “game enabler” through its funding capability; it will be abbreviated in the graphical representation as \( (G) \).
Public Opinion

If the long term effects of a programme involving public funding want to be properly caught, some attention has to be dedicated also to the public opinion behaviour and to its effect on public institutions strategies: in fact, that has to be intended as the only counterbalance to government capabilities to fund R&D investments, but it is necessarily a response restricted to the long term effects and then very difficult to be modelled while attempting to describe a three days conference such as ASIME. As it shall be expected, the public opinion was in reality not represented at the conference, and the mentioned counterbalance was therefore missing. The result has been the acceptance of several appealing but expensive proposals to promote asteroids mining, like, for example, the launch of a dedicated space telescope for asteroids observation in the thermal (see Delbo et al, 2016) and infra-red frequency or the wide (and well deserved) support to ESA Asteroids Impact Mission (see Michel et al., 2016), which just three months after the conference was unfortunately rejected by the ESA Ministerial Council.

Due to its absence in ASIME and its impact only in the long term scenario, it is then proposed to leave the public opinion player aside this game modelling, and to consider it just as an external observer driving governments’ long term strategies.

Players Summary

Four players are then selected to describe this game:

- Scientist (S)
- Traditional Space Industry (I)
- Asteroids Mining Industry (M)
- Governments (G)

The Player’s Goals

Each player has, of course, different objectives or goals and it is important to correctly identify and rank them to then understand the possible strategic options available to each of them. To maintain the game description reasonable, three ranked objectives will be identified for the already described actors.

Scientists’ Goals

As we have commented in the introduction, after the extended sociological critics to the scientific method elaborated during the seventies, the sociological constructivism has made it clear that scientists don’t only pursue epistemic objectives, but they take their decisions also to increase peers’ recognition and economical funding of their work, amongst other ‘social’ or ‘non-epistemic’ goals. Nevertheless, as it is argued in Zamora Bonilla (2002, 2009), it is reasonable to assume that the norms regulating the behaviour of researchers are designed so as to make the pursuit of epistemic goals a primary (though not exclusive) motivation in science. To simplify, we shall consider the following three goals of scientists:

1. Knowledge: It represents the aim to satisfy the scientist’s desire of increasing our knowledge of nature (epistemic goal)
2. **Recognition**: This is the aspiration to obtain recognition of his/her work by his/her peers and become then a reference in his/her field of study (social goal)

3. **Funding**: The real life goal, that is the need to receive funding to support his/her research and then having the possibility of satisfying the first two objectives (economic goal)

### Space Industry’s Goals

Traditional industries can have different missions and organisations, but if they don’t generate profits they are not sustainable. This is as simple as it is. Once this first goal is accomplished, then company mission comes into play, and we can say that an engineer working in the space sector will certainly ask to the genius of the lamp to see some device he has worked on flying in a real mission; this wish can be summarised, in a more general way, as the wish of implementing technology and it has interesting similarities, sociologically, to both scientists’ knowledge and recognition desire. Finally, a company has to look for the future, and will then be interested in strategically positioning itself on the market to keep its business and mission alive also in the future.

The three identified objectives for the traditional space industries are therefore described as:

1. **Profit**: It cannot be forgotten that generate profit it is the main purpose of any private company (economic goal)

2. **Technology**: Engineers live to produce devices, this is both how they satisfy their aspiration of generating knowledge that contributes to humanity’s wellbeing (epistemic goal) and how they obtain recognition by their peers (social goal)

3. **Positioning**: A company can reduce the profit it obtains from a certain activity in view of a foreseen strategical advantage expected in the future via a market positioning (strategic goal)

### Asteroid Miners’ Goals

The asteroids mining companies are private firms, so, in principle, they should be subject to the same goals described for the traditional space industries. Nevertheless their mission is somehow different, especially when considering the horizon time of the expected investments benefit: it is clear that, when planning the asteroids mining business, nobody expects real profits in the short term, so the benefit goal is somehow distorted as it is moved to the long term objectives, while, in the short term, it is replaced by the need of develop a new breakthrough technology or, at least, to obtain an advantageous positioning in the space mining market.

The three space miners’ objectives are the defined as:

1. **Technology**: That is the key goal to give the company the most strategic asset and advantage with respect to the competitors (strategic goal)

2. **Positioning**: In a very reduced market, it is fundamental to establish oneself in a dominant positioning and to maintain it (strategic goal)

3. **Benefit**: In the long term, also space mining companies are needed to generate benefit to be shared with their investors (economic goal)
To Mine or Not to Mine?

Government’s Goals

In the context of this analysis, public institutions basically aim to promote the leadership of their beneficiaries (territorially defined) in terms of knowledge and technologies. They also need to somehow respond to the public opinion instances, but, as already anticipated in the previous section, this aspect will not be considered in the context of the current study.

The government objectives are then defined as a twofold goal at the same level of interest:

- **Knowledge**: To position the beneficiary country (or countries in case of EU) in a leadership position within the research community (strategic goal)
- **Technology**: To provide the beneficiary country (or countries in case of EU) with the means to achieve breakthrough technologies (strategic goal)

The Players’ Strategies

To pursue its objectives, each player can put in place several moves that can be summarised here in a schematic way as:

1. The possibility to partner with other players or to compete against them
2. The option, not available to all players, to fund activities internally or to grant financing to other players. This is a key feature of techno-science investigation because their research areas are usually highly innovative and then not directly market profitable, needing then dedicated investments to cover this gap.

We will start the strategies description from the government and the space miners, since they are, thanks to their financing capabilities, the game enablers from the economic point of view.

Even with this simplified description, the game will already become complex enough to be difficult to handle, but the proposed separation among partnerships and financing strategies will open the door to valuable game solutions without oversimplifying its complexity.

Government Strategies

When we talk about advanced techno-science investigation, the government is the main game activator. Very innovative research and technology developments have very often to rely on public funding to take place, especially in their initial steps: the game would be immediately over if the funding was suspended when market profitability is still far to come.

The government strategies are then defined by the possibility to grant money or not to the players which can satisfy its goal by generating knowledge or technology. These strategies are:

1. **Finance Both Science and Industry to Obtain Both Knowledge and Technology**: this is what every public institution in principle wants, because it would guarantee both its objectives. Of course real life put limits on funding capabilities and this strategy is not always possible.
2. Finance only science to obtain only knowledge. When the available budget is not sufficient to fund both of them, the government could decide to finance either only science or only industry. In this
first case the priority is given to basic research, maybe because the considered research domain is considered still immature to provide a working technology and it is preferred to first consolidate the scientific knowledge of the area.

3. Finance only industry to obtain only technology. We are again in a scenario with limited budget availability, but this time the priority is given to industry: the technological maturity of a certain device is considered enough advanced to deserve public funding to complete its development process and to achieve higher technology readiness levels.

4. Do not fund anybody (and, of course, obtain nothing). This is definitely a worst case scenario for the techno-scientific investigation: the considered area of research is not judged strategically interesting by public institutions and it is abandoned.

Asteroid Miners Strategies

The asteroids miners can play a double game: they could both play the financing game, by funding science and/or industry to obtain knowledge and technology, and they could partner or compete with other space miners. In general they will not be interested neither in partnering nor in competing with scientists and/or traditional space industries, because they have very different priorities, as presented in the previous section.

For what concerns the financial game, they can very much act as the government granting money or not to the players which can satisfy its goal by generating knowledge or technology. But, differently from governments, they can also decide to develop themselves certain areas of investigation, especially the technological ones. The miners' financial strategies can therefore be described as follow:

1. Finance both science and industry to obtain both knowledge and technology. As for governments, if sufficient budget is available, the space mining industry can subcontract development activities to both science and industry.

2. Finance only science to obtain only knowledge. Differently from governments, this scenario is more likely to happen for space mining industry, because these firms could very much interested in developing themselves the technology needed for asteroids mining, since this would increase their independence from other industrial players.

3. Finance only industry to obtain only technology. As a counterpart of option “b”, this is an unlikely scenario for space miners’ financing strategies, because it would mean to give up both advances in science knowledge and independence at industrial level. Nevertheless it is far to be an impossible option, because asteroids mining requires such complex technologies, needing such long development times, that it could be worth it to rely on external and consolidated providers.

4. Do not fund anybody (but, maybe, still obtain something). This is a much desired option for the asteroids miners, but only if governments have already covered the financing in the areas of interest. If that is not the case, this scenario would leave space miners with open gaps in science and/or technology.

On the other hand the space miners can also play the partnership/competence game, deciding if they want or not partners with other miners:
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1. Compete with other miners to pursue better market positioning. At the moment when this text is being written, only two players are present as space miners, and the most probable scenario is the one where they compete against each other.

2. Partner with other miners to increase their funding capability. A strategical alliance between two competitors would certainly increase their financing capabilities and this could be critical for some very complex technologies. This option is more probable in an extended market than in the case of few players.

Space Industry Strategies

Traditional space industries can also play a twofold game, having both the possibility to decide if partner or compete with scientists and other industries, and the capability to invest money for internal research to then obtain a better market positioning.

From the financial point of view, nevertheless, industry has more reduced options than government or miners, because they don’t have any interest in funding other players. The industry financing strategies are then:

1. Internal funding to obtain a better market positioning. If certain technology is considered profitable in the long term, a company could decide to dedicate part of its benefit to develop such technology, with the hope of positioning itself as the market leader for that technology exploitation.

2. No internal funding to pursue higher profits. A private company investment is always done at the price of reducing the company’s profits, which is the primary goal for each private firm. Therefore it is not unlikely that industries decide not to invest money, even for promising technologies, if the economic conditions do not allow them to do that.

But industries also have to take another very important decision when facing public or private competitions for contracts: they have to structure a team to maximize both the chances to win and the future project profit. These two goals are usually contradictories because contract award probabilities are generally higher for industrial consortiums covering different areas of expertise, but the benefit is of course higher if the profits have to be split with less partners. Furthermore, industries have the possibility to partner both with other companies and with science teams: in the second case there is no market conflict, because industries and scientists usually cover different areas of expertise and pursue different goals, but when assessing the possibility to partner with industries, a private company has always to evaluate the partnership impact in the other industry market positioning, to avoid give it advantages for future competitions.

Considering then the possible combinations of the described options, the partnership strategies available to industries are:

1. Compete with both scientists and industries. In this scenario a private company decides to participate alone to a competition: its chances to win could be lowered by this decision, but, in case of award, the profit will be 100% for the company

2. Compete with scientists and partner with industries. In this case a 100% industrial consortium is built up, leaving aside scientific teams; it could be the case of competitions for a pure technological development where the theoretical basis of the activity is already very well consolidated.
3. Partner with scientists and compete with industries. This is a very probable scenario for techno-science projects: the industrial and scientific teams complete each other with a net split of responsibilities that is beneficial for both of them, without helping competitors positioning in the market. Usually in this scenario the industrial team take charge of the project management and of the biggest money share.

4. Partner with both scientists and industries. If a very complex competition has to be responded, a bigger team could be needed to cover a wider set of expertise areas. This is not all an unlikely scenario, and it is very typical in European Commission H2020 programme.

**Scientists Strategies**

Differently from all the other players, scientists do not usually manage any internal funding to finance their activities, relying only on external grants. Their strategies are then reduced to the possibility to partner or compete with other scientists and/or industries. As for the industries a decision has to be taken assessing the increase in the award possibilities against the share of funding and, more important, against the obtained peers’ recognition. When a scientific article has to be written, the competition to be first author of the publication has an important part in the decision making process and in the partnerships selection.

The available strategies for scientists are then defined as:

1. Compete with both scientists and industries. A scientific team decides in this case to not form any consortium and try to keep for itself both the entire project funding and the full research recognition.
2. Compete with scientists and partner with industries. The scientific team talks to some industrial partner to establish a collaboration to participate in the competition. It has the additional advantage to leave the project management (not at all interesting for them) to the industry and it has no internal competitors in the future results disclosure.
3. Partner with scientists and compete with industries. If a certain competition requires diverse and pure scientific competences, two scientific teams can establish a partnership without involving any industrial partners.
4. Partner with both scientists and industries. As already described for industries, this is the case of complex projects, such as EC H2020, that requires big teams of both scientific and industrial members.

**Payoffs**

For the partnership strategies of each player, the payoffs are evaluated to then build in the next step the game matrices. This exercise is limited to the partnerships aspects and it is then not extended to financing one because that is rather a game enabler than a strategic choice: it will then be directly treated in the next section with the “tree” technique instead that with the matrices one. As already anticipated in the previous sections, this choice will allow having a much more manageable game both for the authors and for the readers.
To Mine or Not to Mine?

Scientists’ Payoffs

According to the strategies and the objectives described in the previous sections, the payoff matrix for the scientists could be defined as shown in Figure 3.

1. Compete with both scientists and industries means working in isolation and it then reduces the amount of knowledge that can be acquired, while increasing the peers’ recognition and the funding share.
2. Compete with scientists and partner with industries increases the chances of developing new technologies and to validate the group theories, while the price of working with industry always means accepting a reduced share of funding.
3. Partner with scientists and compete with industries is worst in terms of peers’ recognition, because it implies to share the glory, but it is certainly advantageous in terms of knowledge and it could also be good as funding share (scientist partners are not as greedy as industry ones)
4. Partner with both scientists and industries is certainly good in terms of knowledge but it is definitely not in terms of peers’ recognition and the funding share.

The same options are ranked in the Figure 4.

Space Industry Payoffs

In the same way the space industry payoffs matrix would be as illustrated in Figure 5.

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Figure 3. Scientists payoff matrix

<table>
<thead>
<tr>
<th>SCIENTISTS</th>
<th>knowledge</th>
<th>recognition</th>
<th>funding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compete (S), Compete (I)</td>
<td>BAD</td>
<td>GOOD</td>
<td>GOOD</td>
</tr>
<tr>
<td>Compete (S), Partner (I)</td>
<td>GOOD</td>
<td>GOOD</td>
<td>BAD</td>
</tr>
<tr>
<td>Partner (S), Compete (I)</td>
<td>GOOD</td>
<td>BAD</td>
<td>GOOD</td>
</tr>
<tr>
<td>Partner (S), Partner (I)</td>
<td>GOOD</td>
<td>BAD</td>
<td>BAD</td>
</tr>
</tbody>
</table>

Figure 4. Scientists payoff matrix ranked

<table>
<thead>
<tr>
<th>RANKING</th>
<th>SCIENTISTS</th>
<th>knowledge</th>
<th>recognition</th>
<th>funding</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>Compete (S), Partner (I)</td>
<td>GOOD</td>
<td>GOOD</td>
<td>BAD</td>
</tr>
<tr>
<td>2</td>
<td>Partner (S), Compete (I)</td>
<td>GOOD</td>
<td>BAD</td>
<td>GOOD</td>
</tr>
<tr>
<td>3</td>
<td>Partner (S), Partner (I)</td>
<td>GOOD</td>
<td>BAD</td>
<td>BAD</td>
</tr>
<tr>
<td>4</td>
<td>Compete (S), Compete (I)</td>
<td>BAD</td>
<td>GOOD</td>
<td>GOOD</td>
</tr>
</tbody>
</table>
To Mine or Not to Mine?

1. Compete with both scientists and industries means, also for industry, working in isolation and it then reduces the possibilities to develop new technology and to obtain interesting market positioning, while increasing company’s profit.

2. Compete with scientists and partner with industries increases the chances of developing new technologies but at the price of reducing the profit and sharing the new technology with competitors, which means renouncing to strategical positioning.

3. Partner with scientists and compete with industries is definitely the most rewardable option for industry, since it could simultaneously satisfy all its objectives. The absence of direct industrial competitors guarantees both the market positioning and good profits (even if certainly somehow lower than in option “a”), while the support form a scientific team offers better chances of developing new technologies.

4. Partner with both scientists and industries is certainly good in terms of technology and, depending on the team structure, it could also be satisfactory for positioning, but it is definitely not rewardable in terms of profit.

The same options are ranked in the Figure 6.

But the case where space industry decided to internally fund technology investigation shall also be analysed, because, in this case the payoff matrix would be different (see Figure 7).

1. Compete with both scientists and industries means, again, working in isolation but now the technology developments are guaranteed because of the internal funding and so it is, as a consequence, the market positioning. All goals are accomplished for this option.

Figure 5. Space Industry payoff matrix

<table>
<thead>
<tr>
<th>SPACE INDUSTRY</th>
<th>objective</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>profit</td>
</tr>
<tr>
<td>Compete (S), Compete (I)</td>
<td>GOOD</td>
</tr>
<tr>
<td>Compete (S), Partner (I)</td>
<td>BAD</td>
</tr>
<tr>
<td>Partner (S), Compete (I)</td>
<td>GOOD</td>
</tr>
<tr>
<td>Partner (S), Partner (I)</td>
<td>BAD</td>
</tr>
</tbody>
</table>

Figure 6. Space Industry payoff matrix ranked

<table>
<thead>
<tr>
<th>SPACE INDUSTRY</th>
<th>objective</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>profit</td>
</tr>
<tr>
<td>Compete (S), Compete (I)</td>
<td>GOOD</td>
</tr>
<tr>
<td>Compete (S), Partner (I)</td>
<td>BAD</td>
</tr>
<tr>
<td>Partner (S), Compete (I)</td>
<td>GOOD</td>
</tr>
<tr>
<td>Partner (S), Partner (I)</td>
<td>BAD</td>
</tr>
</tbody>
</table>
**To Mine or Not to Mine?**

Figure 7. Space Industry payoff matrix with internal funding

<table>
<thead>
<tr>
<th>RANKING</th>
<th>Strategy</th>
<th>objective</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Partner (S), Compete (I)</td>
<td>GOOD</td>
<td>GOOD</td>
<td>GOOD</td>
</tr>
<tr>
<td>2</td>
<td>Partner (S), Partner (I)</td>
<td>BAD</td>
<td>GOOD</td>
<td>GOOD</td>
</tr>
<tr>
<td>3</td>
<td>Compete (S), Compete (I)</td>
<td>GOOD</td>
<td>BAD</td>
<td>BAD</td>
</tr>
<tr>
<td>4</td>
<td>Compete (S), Partner (I)</td>
<td>BAD</td>
<td>GOOD</td>
<td>BAD</td>
</tr>
</tbody>
</table>

2. COMPETE with scientists and partner with industries has the same payoff presented in the case of no internal funding.
3. Partner with scientists and compete with industries in case of internal funding means pay twice the investment price, once in terms of financing the internal technology development and once by funding also the scientist work. This option loose then the profit goal.
4. Partner with both scientists and industries has the same payoff presented in the case of no internal funding.

The strategies ranking then changes if industry needs to use its internal funding (see Figure 8).

**Asteroid Miners Payoffs**

The asteroids miners’ partnership strategies are very simple and lead to a rather trivial payoff matrix, which is here presented only for the sake of completeness (see Figure 9).

Figure 8. Space Industry payoff matrix with internal funding ranked

<table>
<thead>
<tr>
<th>SPACE INDUSTRY</th>
<th>objective</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Strategy</td>
<td>profit</td>
<td>technology</td>
<td>positioning</td>
</tr>
<tr>
<td>Compete (S), Compete (I)</td>
<td>GOOD</td>
<td>GOOD</td>
<td>GOOD</td>
</tr>
<tr>
<td>Compete (S), Partner (I)</td>
<td>BAD</td>
<td>GOOD</td>
<td>BAD</td>
</tr>
<tr>
<td>Partner (S), Compete (I)</td>
<td>BAD</td>
<td>GOOD</td>
<td>GOOD</td>
</tr>
<tr>
<td>Partner (S), Partner (I)</td>
<td>BAD</td>
<td>GOOD</td>
<td>GOOD</td>
</tr>
</tbody>
</table>

Figure 9. Space Miners’ payoff matrix

<table>
<thead>
<tr>
<th>MINING INDUSTRY</th>
<th>objective</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>strategy</td>
<td>technology</td>
<td>positioning</td>
<td>profit</td>
</tr>
<tr>
<td>Compete miners</td>
<td>BAD</td>
<td>GOOD</td>
<td>GOOD</td>
</tr>
<tr>
<td>Partner miners</td>
<td>GOOD</td>
<td>BAD</td>
<td>BAD</td>
</tr>
</tbody>
</table>
1. Compete with other miners could be bad in the short term technology developments, but it is certainly the only reasonable long term strategy in a market with very few players.

2. **Partner With Other Miners is the Other Way Around:** It provides good short terms results at the price of scarifying the long term goals. This strategy shall be reconsidered in the future in case a considerable number of new players came into this market.

**Government Payoffs**

Government does not have any partnership strategy and then any payoffs matrix.

**RESULTS**

The results presentation will be done in two steps:

1. Firstly it will be presented the result of the financing analysis, presenting the game options through the “tree” technique.
2. Secondly the partnership game matrices will be illustrated

Games in tree-form are solved by the algorithm known as ‘backwards induction’: at each final – right-most– node, those choices that give a lower level of satisfaction or ‘utility’ to the relevant player are deleted, and then we proceed to the next player’s choice by considering the utility she gets when the player in the deleted option has made her choice. Games in matrix-form are solved by looking the ‘Nash equilibria’: in each column, we look for the choice that the player in the rows would make if that column were chosen by the other player, and we select that (or those) row(s); we repeat the analysis by starting with the rows and looking for the column player’s choices. Nash equilibria (there can be more than one) are those boxes that are selected in this way by both players.

**Financing Analysis**

This is a preliminary and necessary step in the techno-science investigation because the studied technologies are generally too immature to be directly sold in the market in a short timeframe. Therefore they need financial support either from public or private institutions; otherwise they would just not be sustainable. This is what in ASIME conference has been identified as the “Science Knowledge Gap” (SKG) focusing then the attention more on the scientific contribution than on the technological one.

In the specific instance of the space mining the principal investors will be the governments or the space miners themselves which can fund industry and/or scientists; as already discussed, also the private space industry can decide to put some money into the game by the mean of internal funding of technology research. The full tree of possible options is then depicted in Figure 10.

Nevertheless it is very likely that the space miners’ funding will finance only the uncovered areas by the governments, and that the private space industries will authorise internal funding only if they do not receive other money. The tree would then be simplified in the following structure of 9 branches (see Figure 11).
In this figure a number is assigned to each branch and with green/red colours it is indicated whether industries and science receive funding or not: the main difference between these two players is that industries can always have funding because they have the possibility to access to internal financing (in the figure light green instead of dark green), while scientists are exposed to the risk of not having money.
to perform their research (red). In this case the techno-science game is considered to be over, because both industry and science are needed.

But let’s go through the different branches one by one:

1.  All funding from government: very likely scenario as in ESA or EC projects (i.e. H2020)
2.  Scientists receive funding from government and miners sponsor industries: very unlikely scenario since miners would probably try to develop technologies themselves
3.  Scientists receive funding from government and industries accede to internal funding to stay in the space mining market: possible scenario
4.  Governments fund only industries (i.e. ESA programmes) and miners fund scientists to cover the “Science Knowledge Gap” (SKG): very likely scenario and one of the possible ASIME outcome.
5.  Science has no funding: techno-science game is over.
6.  Miners act like governments and fund both science and industry: very unlikely scenario.
7.  Miners pay scientists for knowledge, and industries accede to internal funding to stay in the space mining market: possible scenario
8.  Science has no funding: techno-science game is over.
9.  Science has no funding: techno-science game is over.

The same information is graphically presented in Figure 12.

If we then prune the more unlikely and the game over branches, four scenarios remain active:

1.  **Funding Scenario 1 (Highly Possible):** Governments fund both science and industry
2.  **Funding Scenario 2 (Highly Possible):** Governments fund industry and miners fund scientists

*Figure 12. Financing game: reduced tree with results*

*For a more accurate representation see the electronic version.*
3. **Funding Scenario 3 (Possible):** Governments fund science and industry uses internal resources to stay in the mining market
4. **Funding Scenario 4 (Possible):** Miners fund science and industry uses internal resources to stay in the mining market

**Partnerships Analysis**

As expected, the most complex and interesting partnership analysis is the one describing the interaction between science and industry. This game matrix is in reality double, as we have seen in the section dedicated to 2.4.2. Space Industry payoffs, since different payoffs appear whether the space industry is making use of internal funding or not (see matrices from Figure 5 to Figure 8). Following then the results obtained in the previous section on the financing analysis, we can configure a twofold game:

1. The funding scenario 1 or 2 game, that is the most probable one
2. The funding scenario 3 or 4, that is possible but not very likely.

In the first case the science-industry game matrix is shown in Figure 13.

The game theoretical analysis of this matrix shows that there are two possible Nash equilibria: the combination of strategies in column 1 and row 3, on the one hand, and the combination of strategies in column 3 and row 2 (e.g., if “Space Industry” chooses the first column, then the third row is the best strategy for “Scientists”, and vice versa). However, as it is straightforward to see, the second of these equilibria (column 3, row 2) is better for both players than the first one (technically, it is “Pareto optimal”). Hence, to the extent that the players can agree beforehand a solution, they will tend to choose the second equilibria. However, the difference in value between both equilibria are not very high for the player “Scientists”, so there would be a chance of seeing that “column 1/row 3” were chosen, if, for example, scientists had adopted in the past a strategy that commits them to mutual partnership, and then “Industry” should have to adapt to that situation. Nevertheless, since in practice there is ample room for negotiation between the players, it is much more likely that they end implementing the optimal outcome: the partnership between scientists and industry, each of them contending with their direct competitors.

![Figure 13. Science-industry game matrix without industry internal funding](image-url)
The situation becomes much more complex if industries have to rely on their own financing: the new game matrix would be shown in Figure 14.

In this case we have three possible Nash equilibria: “column 1, row 3”, “column 3, row 2”, and “column 4, row 2” (the two last ones are equilibria, in part because, if Scientists choose row 2, then the Industry is indifferent between playing column 3 or 4. Now also the situation is more complicated because no one of the three equilibria is a Pareto optimum: the Space Industry would prefer the first one, though scientists would prefer some of the two last ones. This means that the solution of the game, and hence the final outcome of the negotiations, is more undetermined than in the case depicted in fig. 13. However, since the difference in valuation for Scientists between the three equilibria is not too big, the most likely outcome is that the players agree to adopt the first equilibrium (column 1, row 3”).

CONCLUSION

Taking advantage of the proposed analysis, some conclusion can be extracted contrasting the obtained results against ASIME outcome. From the conference wrapping up (described in Amara Graps et al., 2016), two different sets of conclusions can be extracted, one more related with the technical aspects of the workshop and the other one associated with the economical aspect of space mining investigation.

The technical needs identified by the conference participants are mainly focused in addressing the so-called “Science Knowledge Gap” or “SKG”: as it shall be expected, the first steps of a new research field aim to clarify all the unknown aspects of the subject and to cover the correspondent knowledge gap. This is clearly illustrated by two needs identified during the conference: the demand for a dedicated telescope to map asteroids as potential mining targets and the need of new physical measures to characterise them in view of their mining exploitation (i.e. through thermal inertial instead than through light curves). Both of them are science needs but they both entail very complex technological challenges, like the design of new instruments or even the planning of dedicated space missions: therefore, even if the emphasis is put on the science knowledge, the technological component is here a predominant factor for the future activities definition and a “T” should be added to the SKG acronym to consider it (i.e. “Science Knowledge and Technology Gap”, SKTG). In the light of the techno-science epistemology

Figure 14. Science-industry game matrix with industry internal funding

<table>
<thead>
<tr>
<th>Funding Scenario 3-4</th>
<th>SCIENTISTS</th>
<th>SPACE INDUSTRY</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Compete (S), Compete (I)</td>
<td>Compete (S), Partner (I)</td>
</tr>
<tr>
<td>Compete (S), Compete (I)</td>
<td>SCIENCE recognition funding</td>
<td>INDUSTRY profit technology positioning</td>
</tr>
<tr>
<td>Compete (S), Partner (I)</td>
<td>IMPOSSIBLE</td>
<td>IMPOSSIBLE</td>
</tr>
<tr>
<td>Partner (S), Compete (I)</td>
<td>SCIENCE knowledge funding</td>
<td>INDUSTRY profit technology positioning</td>
</tr>
<tr>
<td>Partner (S), Partner (I)</td>
<td>IMPOSSIBLE</td>
<td>IMPOSSIBLE</td>
</tr>
</tbody>
</table>
previously portrayed, it is thus critical to properly describe the interaction between science and industry as an essential component of the space mining sector characterisation; the analysis illustrated in this text through the game theory approach could then be considered as a meaningful contribution to understand this new vibrant area of investigation.

The second critical aspect is the economical one and two questions shall be answered on this: who paid for ASIME organisation? And what is the economic strategy envisaged by the conference participants? Both questions lead us to the financing analysis presented in the previous sections. The conference sponsors have been both public institutions (Government of Luxembourg and ESA) and the space mining industries (Space Resources and Deep Space Industries): this is fully expected in the light of techno-science epistemology, where the optimal strategy has already been identified as the collaboration of science and industry, having either governments or miners’ (or both) investing to cover the SK(T)G. Moreover the envisaged economic strategy largely rely on the promotion of activities funded by public institutions programmes (mainly ESA and EC), which are identified as the necessary techno-science enablers until the market profitability gets closer in time; but here the conference participants reckoned without their hosts, as we have already pointed out in § “2.1.4. Public opinion.” Another important result is the consequence of deficient governments and miners’ funding: in this case we have seen how industry would have to use its internal resources and that this would lead to a different game. The risk of this game is to kill the science-industry collaboration, something that could be a feasible (and sub-optimal) solution of the game, but that, epistemologically, would prevent the techno-science development resulting in a dead-end for the space mining.

To summarise, a complex model has been defined to describe the multifaceted science-industry interaction typical of techno-science; this model has been successfully applied to the fascinating and concrete case of ASIME conference to demonstrate the range of its validity. Moreover, the proposed analysis allows concluding that ASIME shall be considered as a first step in the asteroids mining research and industry construction, a step that privileged the science gap over the technological one. A more important role of technology shall be expected in the future, leading to more complex interactions between science, industry, miners’ and governments.

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**REFERENCES**


