PROPOSAL OF AGENT SIMULATION METHODOLOGY FOR THE PROSPECTIVE ANALYSIS OF MINERAL COMMODITIES MARKETS

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ABSTRACT

The markets of mineral commodities for industrial use (MCI) risk supply shortages in the near future due to a possible restriction policy applied by producers. Therefore, the French government is not reassured because, over the coming decades, such situations may affect French industrial sectors using these products. By taking the world lithium market as an application example, this work aims to contribute to the elaboration of a multi-agent system (MAS) prospective tool, which allows decision makers to evaluate possible supply shortage periods in the world market and in France. The discussion is extended to the aggregates market, another kind of MCI market. The work also aims to evaluate to what extent MAS methodology is accepted in the literature regarding MCI system prospective analysis. This work concludes that a MAS approach could provide a new methodology for analysing MCI markets. However, convincing MCI sectors to use it remains a challenge.

Keywords: mineral commodities markets, multi-agent simulation, lithium market, aggregate resources market

1. INTRODUCTION

1.1. Thematic issues

The markets of mineral commodities for industrial use (MCI) risk supply shortages in the near future. This is true for aggregate resources (AR) markets (a subdivision of MCI markets), e.g. in France (Rodriguez-Chavez 2010) or in the UK (Brown, McEvoy and Ward 2011), and also for metal markets (another subdivision of MCI markets), regarding products such as lithium, indium or rare earths.

In AR markets (in which exchanges often occur at a regional/national scale), the main reason for such risks is objections to mining developments stemming from the perception of negative environmental and socioeconomic effects on surrounding communities and ecosystems (Graedel, et al. 2012). As for metal markets (in which exchanges occur at a national/global scale), risks would dramatically increase in the event of drastic changes to mining or commercial policies towards more restriction of the exportation quota by countries that currently dominate the world market, such as Chile for lithium (Daw and Labbé 2012) or China for rare earths (Roskill 2011, Giacalone 2012). Whereas in Chile this situation is still hypothetical but not impossible, in China such a restriction is already effective.

Given the above situations, the French government is not reassured because in coming decades, such situations may affect French industrial sectors using these products. These sectors are (for AR markets) building and public works or (for the metal markets) automobiles, glass, etc. Thus, in order to successfully implement a policy to deal with these situations, the government (in association with regional authorities in the case of AR markets) suggests the implementation of prospective tools that would help French industrialists regarding the choices to be made towards their future supplies. Such a tool is also expected by the authorities regarding future orientations they may undertake in the French industrial sector.

1.2. Objectives of the work

The objective of the work reported in this paper is twofold and concerns a thematic level and a methodological level.

By taking the world lithium market as an application example, the work at a thematic level aims to contribute to the elaboration of a prospective tool that allows the above actors to answer the following question: *given the uncertainty of supply, how long would a lithium supply shortage last (should the case arise) in the world market as well as in France?* The approach consists, via modelling and simulation by a multi-agent system (MAS) approach (Wooldridge 2009), in creating prospective scenarios of supply shortage in the lithium market due to restrictions decided by a producer, then (a) identifying the set of likely shortage periods that would correspond to these respective scenarios and (b) searching possible alternative supply scenarios to compensate the resulting shortages.

At a methodological level, the aim of the work is to evaluate and discuss the possible interests of applying the MAS approach to MCI applications and to what extent it is currently used in the literature regarding MCI prospective analysis via modelling/simulation. The aim is to show the possibility or not of a methodological transposition of the work on lithium, our application example, to other substances.

2. STATE OF THE ART

2.1. Presentation

In MCI markets and regarding economic prospective market analysis via modelling/simulation, various studies have already been carried out to deal with the supply shortage issue.

Regarding the lithium market, these studies were carried out either by the academic world (Yaksic and Tilton 2009, Gruber, et al. 2011), by lithium consultants (Roskill 2009), by banks ((McNulty and Khaykin 2009), on behalf of the Credit Suisse), or by producing companies ((De Solminihac 2010), for the Chilean company SQM, the current leading lithium producer in the world). In all these studies, production and consumption were respectively extrapolated in an independent manner and the results next compared arithmetically. Thus, there was no mutual driving between the evolution of the supply and the demand values. Furthermore, all the works adopted a global scale as the level of their studies. This approach is the same for metals other than lithium, such as rare earths (Roskill 2011) or copper and magnesium (Andriamasinoro and Angel 2012). In fact, initiating this kind of prospective analysis at a global level is necessary because mineral resources are unequally spread out over the Earth as a whole. However, this is not sufficient. Indeed, efforts to explore the criticality of metals should not consider only the global level, because organizational differences make a uniform analytical approach for all organizational (i.e., global, national and local) levels impractical (Graedel, et al. 2012). In the same way, the risks of distribution may be underappreciated when discussing resources at a global level (Kushnir and Sandén 2012). In particular, knowledge of the quantity available at the global level does not automatically imply that of the distribution per country. Likewise, if the period of likely shortage is known at a global level, nothing says that for a given consuming country it will be the same, since supply behaviour at a production side varies from one producing country to another, depending on its individual and collective interests (Andriamasinoro and Ahne 2013).

As for aggregate resource (AR) markets, the same situation can be observed at a national/regional scale. An example concerns a model called *Antag*, which analysed the supply shortage in AR on the French market: *Antag* was based on a dynamic systems approach (Rodriguez-Chavez 2010). The prospective analysis contented itself with observing the global market flow in France, whereas it has been known for a long time that the opening of production zones is decided at a regional (i.e. more detailed) subdivision level.

As a matter of fact, in MCI, global elements are important indications but need to be refined.

2.2. Proposal

Given this refinement objective, our proposal thus consists in making detailed scales of MCI markets more explicit, i.e. where it would be possible to better evaluate the impacts of the individual behaviour and constraints of producers on the supply shortage periods (if any) of consumers. This is important for the government of a consuming country, especially in a restriction policy context. In metal markets, it consists in passing from a purely world to a more national scale, where the interaction between countries is modelled. Likewise, in AR markets, it consists in passing from a national to a more regional level. Regarding this purpose, the MAS approach is suggested given its capability to represent the complexity of a system at any scale of a territory (Wooldridge 2009). This proposal follows the paradigm of Arthur, Durlauf and Lane (1997) stipulating that what happens in the market economy is actually determined by the interaction of dispersed heterogeneous agents, acting in parallel.

As one may see, the idea of using MAS to model a market is not new in itself (here, 1997). The approach has however never been considered by the MCI field. This absence of MAS in the field insofar can be explained by at least three reasons: (1) the method is not known by the studied field, (2) the method is known (because MAS has existed since the 1990s) but its use has always been considered as not indispensable or (3) its use has been considered as indispensable but its development is too difficult.

As announced in the introduction, the world lithium market has been chosen as an application example, given the importance of this metal in electric vehicle batteries (Gruber, et al. 2011). However, as the discussion throughout the paper will concern MCI markets in general, not only metal markets, the AR market situation, at a regional/national scale, will be also resumed in the discussion section (Section 5.2).

3. MODELLING OF THE EXAMPLE

3.1. Data sources

This lithium example uses international trade data from (GTIS 2012) as data sources. The GTIS data presents flows between producing countries and transit countries (i.e. countries connecting producers and consumers) as well as between transit countries and consuming countries. It should be noted that for various reasons (administrative, geographical, etc.), a given consumer can be supplied by the same producer via several transits.

The chosen data are on a quarterly timescale. This scale was preferred to an annual timescale because it increases the number of observations during the statistical tests.

Finally, the prospective period of the simulation here begins in 2013. The historic period is situated between 2005 and 2012, a period when the lithium data necessary for this work are available.

3.2. Hypotheses

As for the hypotheses of the model, the settings below have been adopted.

First, in order to better exploit the GTIS data, our market model will integrate not just producing and consuming countries obviously but also transit countries and will work "as if" consumers send their demands to transits even if, in reality, they directly address producers, which then send the product to the transits.

Second, for the moment, we only focus on the market of lithium carbonate (Li_2CO_3) and not on the other lithium compound markets such as lithium hydroxide (LiOH) or lithium chloride (LiCl).

Third, even if we integrate producing countries, we do not use either export or production figures. Indeed, in the GTIS data, the figures for exports and imports at a given time are not always identical for reasons of transport delay, administrative procedures, etc. Thus, we only say that a producing country *supplies* the quantity effectively received by a consuming country at that time (after possibly having applied preliminary restrictions, during the scenarios).

Fourth, in the model to be built, all chosen producing countries supply all chosen consuming countries, but with (obviously) different quantities, including 0.

3.3. Modelling

A country is modelled as an agent, which is either a producer (*pc*), a consumer (*cc*), or a transit (*tc*). The system contains η_{pc} producers, η_{cc} consumers and η_{tc} transits. A country may be in the following context: *Normal*, *Restriction*, *Compensation*, *Waiting* and *Maintenance*. At the beginning of the simulation, each country is in a *Normal* context.

The model also integrates agents called *ambassadors*. An ambassador $A(c1 \leftrightarrow c2)$ is a delegate agent that handles the flow exchanged between the countries *c1* and *c2*. The concept of ambassadors has been introduced because, given the complexity of the internal and external behaviours of a country (as will be detailed later) and the topology of the system in general, it seems difficult for us to describe the exchanges between *c1* and *c2*, in *c1* and *c2* at the same time; especially that, for a given *c1*, the mode of calculation of the exchanges changes from one *c2* to another. A decentralisation (delegation) of the description of the exchanges consequently seemed more appropriate to us.

Finally, communication between the agents is formally done via the exchange of events. They take the form *event*(*s*, *r*, <*q1*, …, *qn*>) where *s* is the sender, *r* the recipient and <*q1*, …, *qn*> a list of values to transfer from *s* to *r*.

3.3.1. Formalisation of a normal context

The normal context is the market context of a supply without restriction. Here, all agents are in a *Normal* context. In this context, the interaction between countries and ambassadors, at each time step of the market simulation, occurs by following the four stages below, in which the first two points concern the demand stage and the last two points concern the supply stage.

Stage 1: At the beginning of a time step, each consumer cc_k, $k \in \{1, \eta_{cc}\}$, asks its ambassadors $A(tc_j \leftrightarrow cc_k)$, $j \in \{1, \eta_{tc}\}$ to calculate the quantity $d(tc_j \leftarrow cc_k)$ to demand from all producers pc_i, $i \in \{1, \eta_{pc}\}$, the supply of which will next transit via the country tc_j. Once each $d(tc_j \leftarrow cc_k)$ is calculated, each $A(tc_j \leftrightarrow cc_k)$, $k \in \{1, \eta_{cc}\}$ sends that demand to tc_j. For now, a demand over time is calculated via two steps.

The first step consists in interpolating the time series $S_{d(tc_j \leftarrow cc_k)}$ of the GTIS data related to the demands from cc_k to tc_j between 2005 and 2012, in order to obtain a regression line, which would describe and prolong that demand evolution. Let us note this interpolated value $i(tc_j \leftarrow cc_k)$. Its evolution may take a linear, logarithmic, exponential or average shape.

The second step consists in removing, from the resulting interpolation, the current available stock $A(tc_j \leftrightarrow cc_k).s$ that $A(tc_j \leftrightarrow cc_k)$ already has. After this operation, the stock is naturally decreased. In case it becomes negative, it is set to 0 and the lacking quantity is included in the demand (given the intention to avoid supply shortage i.e. a negative stock).

The process of Stage 1 is summarised in Equation 1 where $cc_k.\sigma_d$ is the sum of the quantities to be demanded by a cc_k to all tc_j.

$$\begin{aligned}
&\text{a) } d(tc_j \leftarrow cc_k) = max(0, i(tc_j \leftarrow cc_k) - A(tc_j \leftrightarrow cc_k).s)\\
&\text{b) } A(tc_j \leftrightarrow cc_k).s = max(0, A(tc_j \leftrightarrow cc_k).s - i(tc_j \leftarrow cc_k))\\
&\text{c) } cc_k.\sigma_d = \sum_{j=1}^{\eta_{tc}} d(tc_j \leftarrow cc_k)
\end{aligned} \quad (1)$$

Stage 2: When tc_j has received, from all the cc_k, the demands $\{d(tc_j \leftarrow cc_1), \ldots, d(tc_j \leftarrow cc_{\eta cc})\}$, the sum of which is noted $tc_j.\sigma_d$ (Equation 2.a), it transfers them to each ambassador $A(pc_i \leftrightarrow tc_j)$, $i \in \{1, \eta_{pc}\}$. The ambassador then calculates, from these demands, the part $d(pc_i \leftarrow tc_j)$ for which pc_i will have to respond. This part is here calculated as being a linear combination of all demands $d(tc_j \leftarrow cc_k)$, $k \in \{1, \eta_{cc}\}$. It is formulated in Equation 2.b in which K_{ij}^d and α_{ijk}^d are the parameters of the linear equation, obtained by a linear regression on the GTIS data corresponding to respective variables

$$\begin{aligned}
&\text{a) } tc_j.\sigma_d = \sum_{k=1}^{\eta_{CC}} d(tc_j \leftarrow cc_k)\\
&\text{b) } \forall (i \in \{1, \eta_{pc}\}, j \in \{1, \eta_{tc}\}),\\
&\qquad d(pc_i \leftarrow tc_j) = K_{ij}^d + \sum_{k=1}^{\eta_{CC}} \alpha_{ijk}^d * d(tc_j \leftarrow cc_k)\\
&\text{c) } tc_j.\sigma_d' = \sum_{i=1}^{\eta_{pc}} d(pc_i \leftarrow tc_j)\\
&\text{d) } tc_j.\tau = tc_j.\sigma_d' / tc_j.\sigma_d\\
&\text{e) } \forall i \in \{1, \eta_{pc}\},\ d(pc_i \leftarrow tc_j) = d(pc_i \leftarrow tc_j) * tc_j.\tau\\
&\text{f) } A(tc_j \leftrightarrow cc_k).h = d(tc_j \leftarrow cc_k) / tc_j.\sigma_d
\end{aligned} \quad (2)$$

described by Equation 2.b. Next, as a linear regression generally generates a residual error, it often happens that the sum $tc_j.\sigma_d'$ of these (calculated) parts may be different from the initial sum $tc_j.\sigma_d$ of the demands from which these parts have been calculated An adjustment must then be made by tc_j regarding each $d(pc_i \leftarrow tc_j)$. Equations 2.d to 2.e show how to proceed, with $tc_j.\tau$ the ratio between $tc_j.\sigma_d'$ and $tc_j.\sigma_d$,. In parallel to all of these operations, $A(tc_j \leftarrow cc_1).h$ is calculated (Equation 2.f). It corresponds to the market share of the quantity supplied to cc_k via tc_j. The interest of this variable will be detailed in Stage 4.

Stage 3: When the demand arrives at each pc_i, the latter, in response, calculates the total supply $pc_i.\sigma_s$ it will provide all consumers. In the present normal context, $pc_i.\sigma_s$ is the same quantity as the sum $pc_i.\sigma_d$ of the demands $d(pc_i \leftarrow tc_j)$, $j \in \{1, \eta_{tc}\}$. This supply is then sent to all tc_j via their respective $A(pc_i \leftrightarrow tc_j)$. Equation 3 summarises the process. It should be noted that a pc_i has a maximal supply capacity $pc_i.\mu$. In this context, it corresponds to the maximum of supplies existing over time for pc_i. The interest of this variable will be detailed in Section 3.3.2).

$$\begin{aligned} &\text{a) } pc_i.\sigma_d = \sum_{i=1}^{\eta_{pc}} d(pc_i \leftarrow tc_j) \\ &\text{b) } pc_i.\sigma_s = pc_i.\sigma_d \\ &\text{c) } pc_i.\mu(t) = max(pc_i.\mu(t-1), pc_i.\sigma_s) \text{ with } pc_i.\mu(0) = 0 \end{aligned} \quad (3)$$

Stage 4: Finally, when tc_j has received the supplies from $pc_i.\sigma_s$, $i \in \{1, \eta_{pc}\}$, the sum of which is noted $tc_j.\sigma_s$, it calculates and transfers to each cc_k its part, via the ambassador $A(tc_j \leftrightarrow cc_k)$, $k \in \{1, \eta_{cc}\}$. The part to be transferred is determined by $A(tc_j \leftrightarrow cc_k).h$, obtained in Equation 2.f. $A(tc_j \leftrightarrow cc_k).h$ takes this opportunity to update its stock according to the supply it has obtained. Equation 4 summarises the process in which $cc_k.\sigma_s$ is the sum of the quantities supplying cc_k from the different tc_j, $j \in \{1, \eta_{tc}\}$ and $cc_k.s$ the total stock of cc_k.

$$\begin{aligned} &\text{a) } s(tc_j \rightarrow cc_k) = tc_j.\sigma_s * A(tc_j \leftarrow cc_k).h \\ &\text{b) } A(tc_j \leftarrow cc_k).s = A(tc_j \leftarrow cc_k).s + s(tc_j \rightarrow cc_k) - i(tc_j \leftarrow cc_k) \\ &\text{c) } cc_k.s = \sum_{j=1}^{\eta_{tC}} A(tc_j \leftarrow cc_k).s = cc_k.\sigma_s - cc_k.\sigma_d \end{aligned} \quad (4)$$

3.3.2. Formalisation of a restriction context

Let us now assume that, as of an instant t_s, a producer pc_r decides to restrict its supply of $pc_r.\rho_s$ points (with $0 < pc_r.\rho_s \leq 1$). In this case, pc_r changes its context from *Normal* to *Restriction* and executes an action pc_r.*restrict*(). This action consists in sending an event *restrict*(pc_i, cc_k, < >) to each cc_k, $k \in \{1, \eta_{cc}\}$ to inform them about the restriction. It also consists in sending to each other producer pc_i, via their ambassador $A(pc_r \leftrightarrow pc_i)$ $i \neq r$, the not supplied partial quantity $pc_r.q_r$ resulting from this restriction. It is given in Equation 5.c. The quantity $pc_r.\sigma_s$ to be supplied to consumers during a restriction is the maximum supply of pc_r diminished by this rate $pc_r.\rho_s$ and potentially further diminished by the total demand $pc_r.\sigma_d$ arriving at pc_r (Equation 5.b).

Following this restriction, the stock $cc_k.s$ of each cc_k will naturally decrease (given Equation 5.b and, in this context, without compensation yet) and finally be in shortage. Let us note $cc_k.\lambda$ the cumulated shortage over time. When $cc_k.s$ is less than 0, it is added to $cc_k.\lambda$ (Equation 5.d). For a country cc_k, the shortage period is that during which its cumulated shortage $cc_k.\lambda$ is below 0 (cf. Equation 5.e, where $cc_k.t_{\bar{\lambda}}$ is the date of the end of the shortage). Finally, Equation 5.f indicates that the shortage to compensate cannot be, in a shortage period, greater than the demanded value. We call the *full shortage* the situation where the shortage is mathematically equal to the negative value of the demand.

$$\begin{aligned} &\text{a) } pc_r.\sigma_d = \sum_{i=1}^{\eta_{pc}} d(pc_r \leftarrow tc_j) \\ &\text{b) } pc_r.\sigma_s = min(pc_r.\sigma_d, pc_r.\mu * pc_r.\rho_s) \\ &\text{c) } pc_r.q_r = pc_r.\sigma_d - pc_r.\sigma_s \\ &\text{d) } cc_k.\lambda(t) = \begin{cases} cc_k.\lambda(t\text{-}1) + cc_k.s(t) & \text{if } cc_k.s(t) < 0 \\ cc_k.\lambda(t\text{-}1) & \text{otherwise} \end{cases} \\ &\text{e) } cc_k.t_{\bar{\lambda}} \text{ is } t > t_s \text{ such that } cc_k.\lambda(t_{\bar{\lambda}}\text{-}1) < 0 \text{ and } cc_k.\lambda(t_{\bar{\lambda}}) \geq 0 \\ &\text{f) } cc_k.\lambda(t) = max(cc_k.\lambda(t), \text{-}cc_k.\sigma_d(t)) \end{aligned} \quad (5)$$

3.3.3. Formalisation of a compensation context

On reception of the restriction imposed by pc_r, each cc_k, $k \in \{1, \eta_{cc}\}$ changes its context from *Normal* to *Compensation* and immediately executes the action cc_k.*makeup*(). It consists in sending, at each time step, and while $cc_k.\lambda < 0$, an event *demandMakingUp*(cc_k, pc_i, <$|cc_k.\lambda|$>) to all the pc_i, $i \in \{1, \eta_{pc'}\}$ with $\eta_{pc'} < \eta_{pc}$ and $i \neq r$. Each pc_i that receives the message, either immediately switches its context from *Normal* to *Compensation* and responds by executing pc_i.*makeup*() described below, or waits for a delay $pc_i.\delta$. In the latter case, it first switches its context from *Normal* to *Waiting* before switching from *Waiting* to *Compensation*, once this delay expires. This delay may be necessary for diverse reasons specific to pc_i: inability to immediately respond, speculation, etc.

During a pc_i.*makeup*(), the total quantity $pc_i.s$ to be supplied *a priori* is given by Equation 6.a. It is calculated as a function of the sum $pc_i.\sigma_d$ of the classical normal demand arriving at pc_i, the not supplied quantity $pc_r.q_r$, obtained from pc_r (cf. Section 3.3.2), the sum of the stocks $|cc_k.\lambda|$, $k=1 \ldots \eta_{cc}$ to be compensated, obtained from all *demandMakingUp* events (cf. above), and the weight $pc_i.\omega$ (in %) of pc_i amongst all compensating producers.

The final value $pc_i.\sigma_s$ to be supplied (compensation included) is then evaluated in Equation 6.b, in which $pc.\rho_p$ is the compensation rate. Equation 6.b stipulates that if $pc_i.s$ is below the capacity $pc_i.\mu$,, it is the final quantity to be supplied. Otherwise, an augmentation of this supply capacity is first required. It corresponds to the minimum between an augmentation by the compensation rate and $pc_i.s$. Then, this minimum is taken for $pc_i.\sigma_s$. Finally, the maximal capacity $pc_i.\mu$ is updated accordingly (Equation 6.c).

When $t \geq t_s + pc_i.\delta$:

$$\text{a) } pc_i.s = pc_i.\sigma_d + (pc_r.q_r + \sum_{k=1}^{\eta_{CC}} |cc_k.\lambda|) * pc_i.\omega$$

$$\text{b) } pc_i.\sigma_s(t) = \begin{cases} pc_i.s & \text{if } pc_i.s < pc_i.\mu(t) \\ min(pc_i.\mu(t) * (1 + pc_i.\rho_p) * pc_i.s \end{cases} \quad (6)$$

$$\text{c) } pc_i.\mu(t) = \begin{cases} pc_i.\mu(t) & \text{if } pc_i.s < pc_i.\mu(t) \\ pc_i.\sigma_s(\text{t}) & \text{otherwise} \end{cases}$$

3.3.4. Formalisation of a maintenance context

On a consumer side, this context starts when a previous making up from compensating producers is finished, i.e. $cc_k.\lambda$ finally becomes ≥0 again while cc_k is still under the pc_r restriction. In a maintenance context, cc_k attempts to stay in the (new) equilibrium situation it has just obtained. Thus, cc_k changes its context from *Compensation* to *Maintenance* and then immediately executes the cc_k.*destock*() action to avoid a surplus stock (since $cc_k.\lambda$ is now >0) at each time step. This action consists in sending an event *demandDestorage*(cc_k, pc_i, <$cc_k.\lambda$>) to all the pc_i, $i \in \{1, \eta_{pc}\}$ and $i \neq r$, while $cc_k.\lambda > 0$. When $cc_k.\lambda$ becomes <0 again due to that action, cc_k.*makeup*() is executed again (but in a maintenance context, not a compensation context), etc. The two actions are alternatively executed over time, depending on the value of $cc_k.\lambda$, so that $cc_k.\lambda$ turns around 0 as closely as possible.

On a producer side, each pc_i that receives the message for the first time also switches its status from *Compensation* to *Maintenance* and alternatively executes pc_i.*destock*() and pc_i.*makeup*(), in reaction to the demands from cc_k. Note that pc_i.*destock*() is identical to pc_i.*makeup*() except that the sum of stocks $cc_k.\lambda$ is for it to be decreased (Equation 7.a) instead of to be increased (Equation 6.a).

$$\text{a) } ts = pc_i.\sigma_d + (pc_i.q_r - \sum_{k=1}^{\eta_{CC}} |cc_k.\lambda|) * pc_i.\omega \quad (7)$$

At this stage of the work, $pc_i.\delta$ and $pc_i.\omega$ are determined by the user, not by the agent. However, a $pc_i.\omega$ can be approximated via the weight provided by GTIS statistical data regarding all pc_i, plus a slight experimental adjustment so that each $cc_k.\lambda$ evolves around 0 during the maintenance context.

4. SIMULATION

4.1. Preamble: the simulation platform

While the statistical tests were performed with the proprietary tool SAS®, the simulation was implemented under the platform *Isatem* (Andriamasinoro 2012). *Isatem* is constituted of a set of components in interaction. Each component possesses a set of properties, a set of handlers, a set of output functions and a behaviour.

The set of handlers manages the input events. For a received event *eventX*, this handler is formally written *OnEventX* (*s*, <*pX1*, …, *pXn*>) where *s* is the component having sent the event and <*pX1*, …, *pXn* > the event parameters. Only a handler *OnTimeChange*() is generic; it allows a component to react to the simulation timer.

The output functions manage the output events. For an event *eventY* to be sent, this function is formally written *FireEventY*(*r*, <*pY1*, …, *pYm* >)) where *r* is the recipient component.

The behaviour possesses the same *OnEventX*() and *FireEventY*() as a component to which it is associated. Actually, a component does not handle an event directly. It sends it to the handler of its current behaviour, having the same name. This mechanism allows a component, at any time, to change its behaviour, which is the way it handles the events, without changing the communication mode between it and its behaviour. Each component possesses a default behaviour. It is then possible, by inheritance (as is defined by the object oriented concept), to *particularize* an *OnEventX*() or a *FireEventY*(). It is what allows two components to possibly have the same properties but totally different behaviours (e.g. a producing country and a consuming country). The body of functions in the default behaviour is either empty or groups the actions common to all the components of the same type (i.e. the *country* type and the *ambassador* type respectively).

4.2. Initialisation of the values for the simulation

The selected producing countries (pc_i) are Chile (*cl*), China (*cn*) and the United States (*us*). These countries are seen by GTIS as being those that regularly supply France with a high quantity (≥25 t/quarter) of Li_2CO_3. We also add a (virtual) country called the *rest of the world* (*rw*). The quantity supplied by *rw* is the world quantity, decreased by that provided by *cl*, *cn* and *us*. Thus, η_{pc}=4.

The selected consuming countries (cc_k) are France (*fr*), the subject of our study and, again, the rest of the world (*rw*). The quantity consumed by *rw* is the world quantity, decreased by that of France. Thus, η_{cc}=2.

Finally, the transit countries (tc_j) are Belgium (*be*), Germany (*de*), United Kingdom (*uk*), Italy (*it*) and the Netherlands (*nl*). The analysis of the GTIS data shows that it is via these transit countries that *cl*, *cn* and *us* transfer their quantities of Li_2CO_3 to France. We also add, again, the rest of the world (*rw*). The quantity transiting via *rw* is the world quantity, decreased by that of *be*, *de*, *uk*, *it*, *nl*. Thus, η_{tc}=6.

All the ambassadors are next naturally created to connect all these countries (*rw* included) in keeping with the formalisms previously described in this paper.

To comply with the data we have chosen in GTIS, the simulation time step is 3 months. Let us note, for example, 2/2019 quarter 2 of year 2019.

4.3. Prospective scenarios

The pattern of the proposed (and currently fictitious) prospective scenario is the following: one assumes that as of 2014 (=t_s), Chile restricts its supply rate by $cl.\rho_s$ points. Following this situation, China accepts to assure compensation at a rate of $cn.\rho_p$ points, and does so immediately, i.e. $cn.\delta=0$. The United States also accepts, with a rate of $us.\rho_p$ points, but only as of 2016, i.e. $us.\delta=8$ (quarters). The purpose of the simulation then consists in varying the values of these rates to find the shortage end date in France and in the rest of the world. A simulation will be formally written (example of France): $fr.t_{\bar{\lambda}} = fr(-cl.\rho_s, +cn.\rho_p, +us.\rho_p)$.

For each simulation performed, the result is read as follows: for each compensation $cn.\rho_p$ and $us.\rho_p$ and for each augmentation $fr.\rho_a$ and $rw.\rho_a$, the shortage end date for France and the rest of the world will be respectively $fr.t_{\bar{\lambda}}$ and $rw.t_{\bar{\lambda}}$. An inverse reading can also be performed: if one hopes that the shortage period does not extend beyond $fr.t_{\bar{\lambda}}$ for France and $rw.t_{\bar{\lambda}}$ for the rest of the world, the United States and China should increase their compensation rate by at least $cn.\rho_p$ and $us.\rho_p$ respectively.

Table 1 shows in detail the list of different scenario instances proposed in this paper. An instance is made of the scenario identifier (written in brackets), the value of

Table 1: List of all the Scenarios, an Instance Being Composed of a Restriction from Chile (cl) followed by a compensation from China (cn) and USA (us)

id	$-cl.\rho_s$	$+cn.\rho_p$	$+us.\rho_p$
(a)	-0.15	+0.3	+0
(b)	-0.4	+0.3	+0
(c)	-0.15	+0.1	+0
(d)	-0.4	+0.1	+0.5
(e)	-0.4	+0.1	+0.1
(f)	-0.1	+0.1	+0

the restriction from Chile and the value of compensation, respectively from China and USA. The value chosen in this table also allows a policy maker to analyse the sensitivity of the lithium market after a variation in important indicators (e.g. here, the diverse rates).

As complementary information regarding the rate variables, our data calibration with GTIS and our additional experiments allow us to allot the values of 35% and 65% respectively for $us.\omega$ and $cn.\omega$.

4.4. Results

Figure 1 first provides an example of how the stock of the rest of the world (i.e. $rw.\lambda$) may evolve throughout the different contexts. The examples taken are from

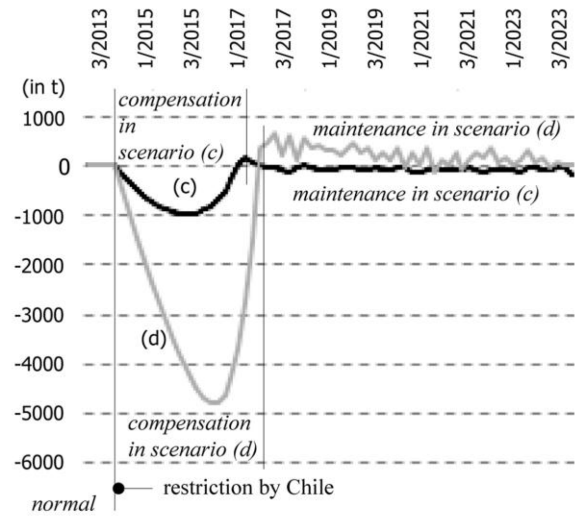

Figure 1: Prospective Evolution of the Lithium Stock in the Rest of the World in its Different Contexts during Scenarios (c) and (d).

scenarios (c) and (d). The figure approximately determines, for *rw*, the end of a normal context, the start and the end of a compensation context (e.g.: around 1/2016 for (c) and 3/2016 for (d)) and the evolution of a maintenance context, in both scenarios.

Figure 2 next shows the shortage end dates obtained for the rest of the world in all scenarios. In this figure, the value of 13,000 (in t/quarter), in absolute value, approximately represents the average demand of lithium of *rw* (according to the GTIS data). It means for example that in Scenario (f), at the peak time of a supply shortage period, there is still a minimal value of around (13,000-5,800) t/quarter of lithium (more than 50%) which are supplied to this consumer. It should be

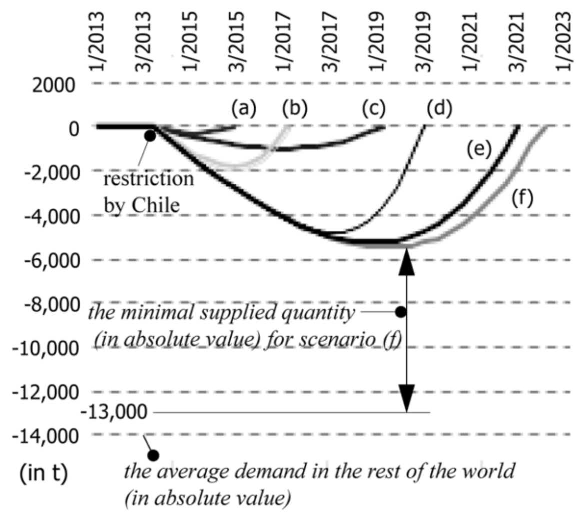

Figure 2: Prospective Evolution of the Lithium Stock in the Rest of the World, for all Scenarios

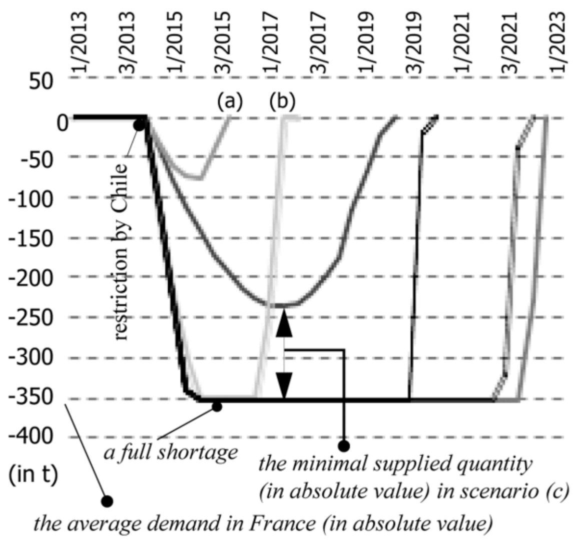

Figure 3: Prospective Evolution of the Lithium Stock in France, for all Scenarios

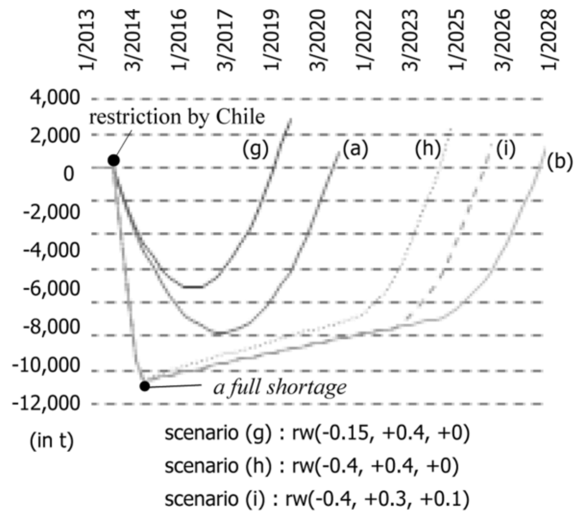

Figure 4: Prospective Evolution of the Lithium Stock in the Rest of the World according to the work (AH13)

noted that in Figure 2 the maintenance stage is no longer shown, for reasons of clarity, but actually, at that context, the shape of the curves of all other scenarios are approximately similar to that of the two scenarios presented in Figure 1.

Figure 3 is the "France equivalent" of Figure 2, with an average demand of around 350 t/quarter (according to the GTIS data). In this figure, France reaches a full shortage in all the scenarios where the Chile restriction is high (-0.4), i.e. (b), (d), (e) and (f), and with a different duration. The reason for this full shortage is that the linear regressions made on the GTIS data result in a behaviour where the model first handles the rest of the world (*rw*) and when the stock is close to 0 again for *rw*, there is afterwards an automatic consideration of France. It should however be observed, in Figure 3, that for France, the transition from a full shortage period to an equilibrium state is then very fast in all the scenarios where a full shortage occurs.

5. DISCUSSION

The results presented previously and in next sections are still being adjusted and validated by the domain experts. However, this current validation does not affect the fact that a progress has been made compared to the state of the art.

5.1. Thematic discussion

If we refer only to the results of these simulations, France does not need to worry about a possible prolonged shortage of its supply in lithium, even following a Chilean restriction. Indeed, even if Figure 3 shows many full shortage situations, at the same time, the rest of the world is still supplied at least around 50% of its needs and adding France to the list of supplied countries should not be a real issue since the French proportion is small compared to that of the rest of the world. This conclusion is also confirmed by the fact that a return from a full shortage to an equilibrium situation is fast for France. From this model to a real-world prospective analysis, it is possible to conclude that possibilities exist for France to avoid a supply shortage. (Daw and Labbé 2012) have already concluded that the risk of shortage is low for France, but they did not however analyse the effects of a scenario of an effective restriction in their study.

Regarding our modelling exercise stage, this work is a continuation of that previously carried out by (Andriamasinoro and Ahne 2013), noted AH13 for short. The simulation results of that work, regarding the rest of the world, are recalled in Figure 4.

The present work is a refined version of that work by (1) introducing a more dynamic interaction between a supply, a demand and a stock (Equations 1.b and 4.b) over the simulation while (2) introducing equations for adjustment (Equations 2.d and 2.e). The goal of the latter is to remove any residuals due to the linear regression processes and to be sure that the quantity demanded by consumers and passing via a transit country is exactly the same as the quantity demanded by this transit country to the producers.

These improvements allow us to implement the maintenance context, which did not exist in AH13, i.e. in AH13 the model could not consider what happened when having reached a return to an equilibrium state after a compensation stage. This possibility of remaining around an equilibrium state (as in the maintenance context) is possible only when considering the dynamic interaction between a supply, a demand

and a stock, which has been introduced only in this work.

These improvements also allow us to discover the possibility for obtaining a more optimistic market than that in AH13, regarding the supply shortage issue. Indeed, if we compare Figure 4 with Figure 2 (i.e. $rw.\lambda$ in this work), the following statements can be observed. First, the end of a supply shortage in the worst scenario of AH13 was 2028 against 2023 here. Second, the minimum supplied value in the best scenario of AH13 (Figure 4.g) practically corresponds to the minimum supplied value in the worst scenario of this work (Figure 2.f). Furthermore, it may be noted that the scenarios (g) (h) and (i) in Figure 4 are no longer represented in Figure 2. The reason is the corresponding supply shortage period of these scenarios is now very short. Thirdly, the worst scenario of AH13 (Figure 4.b) practically indicates an almost full shortage in the rest of the world when Chile restricts by "only" -0.4 (i.e. -40%). In the present work, a full shortage is far from reached, a statement more acceptable given that 60% of the supply is still realized even in a restriction.

Globally, we think as regards the rest of the world that the result in Figure 2 is more realistic than in AH13, at least if our hypotheses are verified. As for France, the conclusion in AH13 is practically the same as that presented at the beginning of this section.

All of these conclusions appear interesting and the present work seems to be an improvement. However, these conclusions should be interpreted with caution whether they concern the best or the worst scenarios. Indeed, as rightly recalled by (Feitosa, Bao Le and Vlek 2011), results obtained in any exercise of modelling complex systems do not represent either precise forecasts or deterministic answers. In addition, we think that in a crisis situation a model cannot always handle all circumstances that may happen and, as such, the situation in the previous work showing a more pessimistic result may occur anyway in a real world, even if it is more disputable at a conceptual level. All in all, the results obtained from this modelling exercise should mainly serve to feed the public debate concerning the subject and the scenarios provided here only aim to offer various potential situations, to make the debate as rich as possible.

5.2. Methodological discussion

Regarding the use of MAS in the MCI field, work carried out by Andriamasinoro, Orru and Pelon (2006) concluded at that time that MAS can be adopted to follow up *only* the possible dynamic evolution of MCI markets at a microeconomic scale (i.e. at a site scale), in which the issue is to follow a population activity and migration (Jonsson and Brycesson 2009). In the case of MCI markets, analysed at a more medium-macroeconomic scale, given that economic indicators are periodically displayed, decision makers already have a better idea of what to do in the future without inevitably using a method such as MAS. This statement has effectively been confirmed over recent years: market models used to handle the supply shortage issue in the MCI field generally rely on purely mathematical or statistical approaches. Such is the case of the works presented in the State of the Art of this paper (Section 2). Let us also acknowledge that in the field of macroeconomics, in which metal markets exist (i.e. at a world level), analysts have always traditionally preferred to rely on conventional economic equilibrium models such as DSGE (Fernández-Villaverde 2010). In no case has MAS been used. According to one policy adviser (Hamill 2010), a motivation towards better use of MAS requires proving to analysts that this method provides something better than they already have.

We think MAS is now in that case and should also be progressively adopted in both aggregate resource and metal markets, due to the reasons explained subsequently.

5.2.1. MAS and metal markets

With regards to metal markets, the economic crisis in 2008-2009, resulting from interactions between local players (individual banks, households, traders, etc.) and which then had repercussions on the world market, has made economists reconsider modelling at a macroeconomics level. Indeed, they observed that models such as DSGE were no longer sufficient to anticipate a crisis situation and that MAS could be a solution (Farmer and Foley 2009). The Economist (2010) review presents this insufficiency as follows: "if conventional models perform well enough in a business-as-usual economy, based only on the existence of an ideal state of equilibrium, there is no equilibrium during crashes. Agent-based models may be more suitable because they make no assumptions about the existence of efficient markets or general equilibriums. Instead, they are focused on the assignation of particular behavioural rules to each agent and large fluctuations and even crashes are inherent to the system".

Supply shortage, the subject of the present work, may be a future market crisis occurrence. Indeed, it includes an important period of disturbances, resulting from individual decisions, but being able to trigger major consequences on the global market and on importing countries.

5.2.2. MAS and aggregate resources markets

With regards to aggregate resources (AR) markets, often analysed at a national/regional level, the main issue of the authorities concerning production in this market is to better identify the future geographical distribution of resources while regarding the environmental and societal constraints of the extraction activity. The idea of having the distribution is to favour the proximity of producers to consumers, thus reducing transport and environmental costs (Brown, McEvoy and Ward 2011). In order to quantify this proximity, a prospective model should then be spatially explicit; a map is in particular often used by geology analysts/authorities as a decision making support (Cassard, et al. 2008). However, a system dynamics approach, as used e.g. by Rodriguez-Chavez (2010) to model AR market flow in France, was not able to represent such a spatiality.

In these situations, we think MAS is more suitable. The idea is, at the start of a simulation, a modeller/user imports into the MAS environment the user thematic maps required by the application. Then, at any time during an on-going simulation where agents interact with the space, it should be possible for an analyst to export this dynamic spatial data as new temporal map data and to import this new data in a tool such as a GIS, for a more in-depth spatial analysis. This proposal is currently being implemented throughout an application in the Seine-Normandie region (France) (Andriamasinoro 2012). The application concerns the prospective analysis of AR flows in that region, by using thematic maps such as quarries (for production), cities (for consumption) and roads (for transport). That work does not currently consider other thematic maps such as geological resources or environmental constraints, necessary information to better identify the exploitable resources area. At a thematic level, this application needs to be improved. Nevertheless, at a methodological level, it already can demonstrate the interest of using MAS for the AR market analysis.

5.2.3. Suggestions for better acceptance of MAS

In addition to her first suggestion in Section 5.2, Hamill (2010) also suggests that it is necessary to demonstrate the value of MAS modelling by showing-by-doing and offering training projects. This is, we believe, the case of the present work: it is an additional MAS application (even if, we agree, not yet sufficient to convince). Yet, regarding MAS acceptance, Andriamasinoro and Angel (2012) suggest favouring the coupling between MAS models and mathematical or statistical models, instead of sticking to a solely MAS approach. This point of view is emphasized by Weyns, Helleboogh and Holvoet (2009), who stipulate that one of the reasons that MAS is not accepted in industry is research in MAS profiles itself as an isolated community and, as such, may create artificial thresholds in convincing people of its merits. A continuation in overcoming this situation should then be carried out over the next years.

6. CONCLUSIONS

The markets of mineral commodities for industrial use (MCI) risk supply shortages in the near future. This is true in aggregate resources markets, as well as in metal markets (lithium, indium, rare earth markets, etc.). Given this situation, the French government is not reassured because in the coming decades such situations may affect French industrial sectors using the products from these markets.

The objective of the work reported in this paper is twofold and concerns a thematic level and a methodological level. At a thematic level, it attempts to contribute to the elaboration of a public policy support tool to help French industrialists as well as the French government to ensure that in forthcoming decades there will always be a continuity of supply in the MCI markets. The application example taken is the world lithium market, but the discussion is also extended to aggregate resources markets. At a methodological level, the aim of the work is to evaluate and discuss the possible interests of applying the MAS approach to MCI issues and to what extent it is actually used in the literature regarding MCI prospective analysis via modelling/simulation.

As regards the thematic level, the model allows us to strengthen the idea that in the event of a supply restriction the risk of shortage in France remains very low or, at least, very limited in time. As for the rest of the world (i.e. the “sum” of the worldwide countries other than France), the shortage periods are more consequent. As an example, for a restriction starting in 2014, the return to an equilibrium state in the worst scenario (high restriction vs. very weak compensation) is 2023. However, this result is more optimistic than what has been found in AH13, a previous work (2030). All in all, both results would serve to feed the public debate concerning the subject.

As regards the methodological level, it has been argued that the MAS approach can implement MCI issues at world, national and regional levels thanks to its inherent hierarchical and spatially-explicit features. The interest in MAS has in particular increased since the economic crisis, generated by individual behaviour, and where conventional economic equilibrium models could not anticipate the crisis. In addition, its spatially-explicit features now enable modellers to introduce thematic maps to better localize the future potential resources where existing models have ignored these spatial aspects. However, despite this promising situation regarding MAS, convincing the actors of the MCI sectors to integrate models from MAS as a decision support tool remains a challenge. Explanations for this state of affairs and proposals for progress regarding MAS acceptance are provided.

7. FUTURE WORKS

In the first place will be the introduction of other variables to possibly explain supply and demand in France. We are thinking in particular of *mining reserves* and *prices*. Secondly, it will be necessary to make the system more complex by introducing the other producing and consuming countries (which will involve, in the model, their "withdrawal" from the virtual country "rest of the world"). Thirdly, a methodological transposition of all the work to other metals will be carried out. There are naturally strategic metals such as rare earths, but one should not completely forget major metals, with iron and steel to the forefront, but also aluminium or copper, which have an economic importance much greater than lithium. Likewise, works related to aggregate resources markets, precisely the Seine-Normandie (France) application, will be continued by adding other thematic maps such as geological resources and environmental constraints as factors to better localise future potential resources in that region.

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