Artisanal and Small-scale Gold Mining in Alga (Burkina Faso): Building a Decision-Aid Model for Development and Governance

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1. INTRODUCTION

Between 2001 and 2004, the BRGM carried out, in close collaboration with the BUMIGEB (the Geological Survey of Burkina Faso), research on ASGMA (Artisanal and Small-scale Gold Mining[1] in Alga), Alga being a site in Burkina Faso, which is considered as a reference for carrying out such work. These studies resulted in the collection of real data (hereafter noted rea_d), which have been synthesised in [1].

Using rea_d as a starting point, we constructed a MAS model aimed at carrying out *prospective research* on answers to the following questions:

q1)- "with regard to *development*, to what extent is it possible to improve the income of the ASGMA population?"

q2)- "with regard to *governance*, to what extent is it possible to reduce the importance of the clandestine gold buyers in the ASGMA?"

However, before carrying out such prospective research, we first had to ensure that the ASGMA (cf. Section 2) model was valid, namely complied with rea_d as closely as possible.

This paper presents both works, by following the "classical" steps: *modelling* (Section 3), *simulations* (Section 4), *discussions* (Section 5) and *conclusions* (Section 6).

2. PRESENTATION OF THE ASGMA

The ASGMA contains two steps: *exploitation* of ores containing gold, and *distribution* of the resulting income.

Exploitation of ores

Exploitation takes place in two areas: the *extraction area* (*EA*) and the *transformation area* (*TA*). Exploitation means the manipulation of ores by the following successive tasks: *extraction* from the shaft (in *EA*), *conveying* (between *EA* and *TA*), *crushing*, *grinding*, *sluice washing*, *winnowing* and *mill grinding* (in *TA*). The final ore then gives *gold dust*.

Each task is performed by a *team of actors*: *miner* actors extract ores; *conveyor* actors carry them to *crushers*, etc. Moreover, each shaft sh has *keepers* and one *shaft owner* so on behalf of which the *miners* in sh work. After a phase of *extraction*, each so subcontracts the transformation of its ore to the actors in *TA*. And since *EA* generally contains several shafts for one *TA*, each task in *TA* possesses a "First In First Out" (FIFO) list, used to temporarily store the ores as and when they arrive from the preceding task.

We have not included the *conveyor* actors in this study since we do not yet have all of the necessary data concerning them.

A task i is noted $\mathtt{T}_i = <\pi_i, \rho m_i, \rho au_i, \eta_i>$ in which:

- the π_i, measured in *kgo/a/d* (i.e. kilogram-ore/actor/day), is the daily *productivity* of each actor performing $\mathtt{T}_i$. It represents the number of kilograms of ore that the actor can, *on average*, manipulate during one day.
- the ρm_i, measured in *%*, is the *ratio of ore* recovered, *on average*, from a task $\mathtt{T}_i$, and introduced in $\mathtt{T}_{i+1}$ (if any). The ratio (100-ρm_i)*%* is either lost due to the nature of the task itself (e.g. *winnowing*), or taken by actors (mostly the *crushers*), as remuneration. Thus, like *miners*, *crushers* also "extract" ores. We call both *ore owners* (or *oo*)[2].
- the ρau_i, measured in %, is the *grade of gold* recovered, *on average*, after an ore has been manipulated by $\mathtt{T}_i$.
- the η_i is the number of actors performing $\mathtt{T}_i$.

An ore introduced in $\mathtt{T}_i$ is formally noted:
$\mathtt{Ore}_i = <\mathtt{oo}, \mathtt{M}_i, \mathtt{W}_i>$ in which:

- $\mathtt{M}_i$ is the *mass* at the entrance of $\mathtt{T}_i$. It is measured in *kgo* or *to* (i.e. ton-ore) with 1 *to* =1000 *kgo*,
- $\mathtt{W}_i$ is the *gold weight* in $\mathtt{Ore}_i$. It is measured in *gAu* (i.e. gram-gold). We note $\mathtt{W}_{dust}$(oo) the gold obtained at the end of the exploitation, carried out on behalf of oo.
- oo is the *owner* of $\mathtt{Ore}_i$.

Distribution of the resulting income

The income is earned daily. That coming from a task $\mathtt{T}_i$ is noted Υ_i, and is measured in *Cfa* (where 1*US$* = ≃500*Cfa*).

1 An "artisanal mine" is a generally informal operation exploiting mineral resources by using mostly manual methods and rudimentary tools.

2 Even though *crushers* are *TA* actors, they are also studied as being *oo* actors. In these cases, we note $\overline{TA}$, the *TA* without the *crushers*.

The income per team

For each team of *oo* actors, the gold W_{dust} obtained during one day is sold to two kinds of buyers: some α_{cland} is sold to *clandestine* buyers, at a price p_{cland} (measured in *Cfa/gAu*), and only the part α_{off}=(100-α_{cland})% is sold to the *official* buyers, at a (less advantageous) price p_{off}. The final income Υ_{oo} is given by Equation (1)-b, in which p_{dust} is the sum of the official and clandestine prices.

$$a)\, p_{dust} = [\alpha_{cland} * p_{cland} + \alpha_{off} * p_{off}]\ Cfa/gAu \qquad b)\, \Upsilon_{oo} = [W_{dust}(oo) * p_{dust}]\ Cfa \tag{1}$$

As for a $\overline{TA}$ team performing T_i, Υ_i is obtained by Equation (2), where π_i is the productivity and φ_i is the *provision* (measured in *Cfa/kgo*) corresponding to T_i.

$$\Upsilon_i = [\pi_i * \varphi_i]\ \ Cfa \tag{2}$$

The income per individual

For each *TA* actor of a T_i, the income Υ_{indiv_i} is merely: $\Upsilon_{indiv\_i} = \Upsilon_i/\eta_i$.

Concerning *EA* actors, the formula is more complex (see Equation (3)). Assume $\sigma\Upsilon_{EA}$ (in *Cfa*), the sum obtained by a given so in one day. At first, so subtracts the cost $\varsigma\varepsilon$ that was necessary for the shaft extraction (e.g. pump rental), plus the Υ of all $\overline{TA}$ actors (i.e. $\sigma\Upsilon_{\overline{TA}}$) to which so has subcontracted the transformation of its ore. Then, so takes, for himself, half of the remaining amount Υ_{EA}, that is, $\Upsilon_{EA}/2$, and finally, he equitably distributes the other $\Upsilon_{EA}/2$ among the η_{miners} and $\eta_{keepers}$ of his shaft.

$$1)\, \Upsilon_{EA} = \left[\sigma\Upsilon_{EA} - (\varsigma\varepsilon + \sigma\Upsilon_{\overline{TA}})\right]\ Cfa \qquad 2)\, \Upsilon_{so} = [\Upsilon_{EA}/2]\ Cfa \qquad 3)\, \Upsilon_{miners} = \Upsilon_{keepers} = \left[\frac{\Upsilon_{EA}/2}{\eta_{miners}+\eta_{keepers}}\right]\ Cfa \tag{3}$$

3. AGENT MODELLING OF THE ASGMA

Presentation of the agent platform

Our agent platform is ADK [2] (for "Agent Developer Kit"), developed by Calderoni with the idea of simulating a society of artificial agents. ADK contains three of the main components generally found in Multi-Agent Systems: *agents*, *objects* and *environment*. Our present work is based on a specialisation of ADK to the world of robots: RDK (for "Robot Developer Kit"), which we have already previously applied to other cases such as the exploitation of quartz in Madagascar [3]or the robot foraging problem [4].

The former version of the model

Initially, ADK managed only individual agents' behaviour. This agent behaviour is based on the triad "*perception-deliberation-action* ". Messages exchanged inside ADK are then called percepts (e.g. visual and voice percepts). The environment is composed of entities that can be agents or objects. Both have properties (respectively noted `ag.prop` and `ob.prop`) in which one can either read values (e.g. for agents, it is noted `ag.prop`→`val`) or write values (e.g. for agents, it is noted `ag.prop`←`val`). The environment also acts as the central medium communication between agents and agents/objects.

The architecture of an ADK agent contains two main parts:

- the *body*, which is in relation with the environment and performs both *perception* and *action* phases.
- the *head*, which contains the *deliberation* phase, whose dynamic is largely inspired from the action selection found in the Maslow model [4].

The dynamic of this deliberation phase is based on the selection of *roles*, followed by that of *real actions*. A role is an abstract representation of actions. The inverse is not true, i.e., an action may exist independently of any role.

Structurally, there are two kinds of actions/roles: *primitive* (PR) which is the fine-grained action, uninterruptible during its execution, and *composed* action (AC), a combination either of PR or of other AC. Roles/actions are connected via either the following types of links: `then` (succession), `xor` (exclusion), `imp` (implication) and `and` (simultaneity). The transition from a role to its real actions is part of `imp`, and `and` is the default connector if no connection is set between two actions/roles.

In addition, ADK has the following factors (illustrated by examples from the ASGMA case):

- the *precondition*, that must be verified before an action/role can be executed. For an agent `ag`, it is a Boolean function determined by the properties of `ag`, or by what it perceives from the environment (or by both), and which *implicitly* determine some of its behavioural patterns. For example, `ag` does not accept `ag.role` ←`keeper` if `ag.sex` →`female`. Women generally prefer roles like `winnower`.
- the *time* when an action/role is planned to be executed. E.g., `extraction` is performed before 4*pm* only.
- the *user settings* : these are like preconditions but are *explicitly* set by users. E.g. a user may want to "force" `ag` so that `ag.role` ←`crusher` even if given its (old) `age`, it is preferable that `ag.role` ←`keeper`.
  The initialisation of an ADK system is also performed via this latter factor.

The advanced version of the model

The previous studies were rather oriented to individual agents' behaviour. In this study we have formally introduced the group level. Like individual agents, group agents also have two parts:

- the *group body*, which physically contains the properties of the group. It can be any object in the environment, chosen by the user of the application.
- the *group head*, which is the "set" of the part of the head of individual agents composing the group, but which plays roles related to the interest of the group.

This new situation leads us to reorganize ADK as four layers that are, from top to bottom:

- the *behaviour* layer that groups all individual and group head activities.
- the *agent* layer that is the previous agent body. Its relation with the above layer is represented by a link named `adopts`, which is actually the abstract formulation of the deliberation process described previously;
- the *object* layer, containing all objects of the system. The agent layer is connected to this layer via two links. The first link is named `has`. A link `agent.has(object)` exists if `agent` actually possesses `object`. The second one is `manipulates` which represents the manipulation of `object` by `agent` (e.g. the tasks in the `ASGMA` case). The instantiation of this link is initially preset by the user.
- the *space* layer, which is a 2D continued environment represented by (`x`, `y`) coordinate via a link named `is_at`. Agents and objects situated in the space layer take geometrical forms such as a circle, polygon, etc.

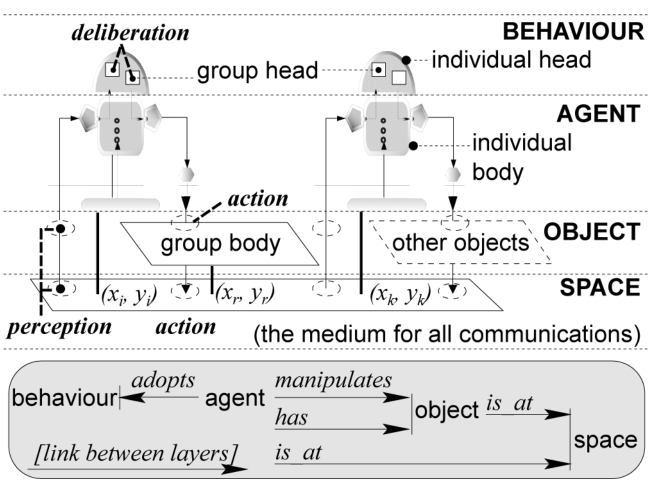

Figure 1: Generic architecture of the ADK agent model that will be applied to the ASGMA

Note : the behaviour layer of the model is based upon the fact that every agent can generically play any role and can possess any objects. The *precondition*, *time* and *user settings* then refine this generic behaviour at application level.

Application of the model to the ASGMA

With regard to the group agent body

In *EA*, the group body is the shaft. In *TA*, the body, for each group, is the zone where this group works. In concrete terms, it is a demarcated area that we call a `taskzone`. The FIFO list of the respective group, i.e. the element that contains the ores normally treated by the group is, for example, physically stored inside this area.

With regard to the group agent head

In the `ASGMA`, the behaviour layer is more focused on group than individual behavioural patterns[3]. Notions like *shaft owners*, *keepers*, *miners*, *crushers*, *grinders*, etc. become roles. They are executed by *agents*, who are actually the translation of the concept of *actors* in a MAS context[4]. These roles are associated with actions, which are the translation of the concept of tasks in a MAS context.

An additional role exists in *TA* : the group *representative*. When a `taskzone` has finished treating one element `ore_el` of its FIFO, and `ore_el` is still in transformation, the role of the *representative* is to transfer it to the next `taskzone`. Otherwise, if `ore_el` is the final task that gives $\mathtt{W}_{dust}$, the *representative* sends it to its owners.

Figure 2 presents a (partial) view of the application of ADK to the `ASGMA`. For reasons of space, we only have taken the case of *winnowers* as an example on the *TA* side. The action `rest`, resumed from a previous application [4], is only given here to show the possible consideration for individual actions by the model.

4. SIMULATIONS

It should first be noted that, like `rea_d`, we also have `sim_d` on the simulation side. Any parameter `x` may be either a `rea_d` (and noted $\mathtt{x}_{rea}$) or `sim_d` (and noted $\mathtt{x}_{sim}$).

Simulation objective 1: validation of the model

Our simulations were firstly aimed at validating the model. For this purpose, the chosen output to be followed was the set $\{\Upsilon_i\}$ per role `i`, because the `ASGMA` is adopted to reduce the poverty of the population. The set $\{\mathtt{in}_{rea}\}$ of our inputs is composed of parameters such as ρm_i, ρau_i, π_i, φ_i, and η_i.

Action: The validation consists in *empirically* searching, via what we call *trial-and-valid* (noted `tav`) simulation runs,

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3 The agents are however capable of performing individual actions such as *buying food*, *caring for persons*,, etc. already used in previous applications. These actions are important for cases like the impact of the ASGMA on the health of miners, an analysis that nevertheless falls outside the scope of this study.

4 The reason for the distinct usage of "agent" and "actors" is because the presentation of the ASGMA in Section 2 must be independent of the fact that it will next be translated into an agent model. The formal structure remains valid for any other modelling approaches.

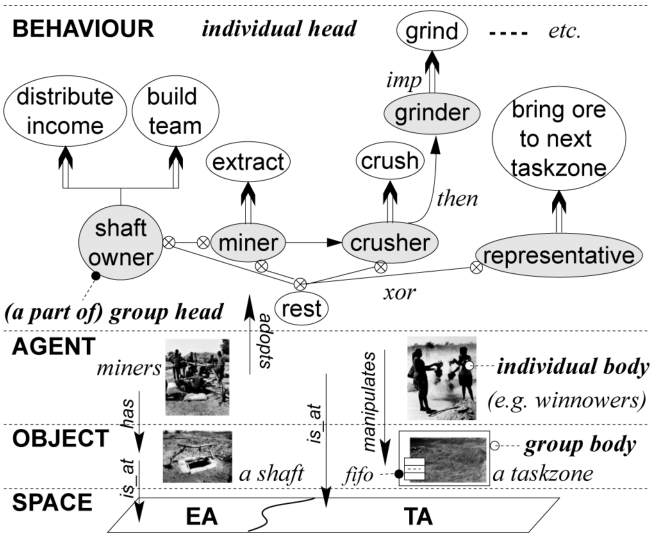

Figure 2: A view of the model, applied to the ASGMA with winnowers as an example on the TA side.

the set $\{\texttt{in}_{sim}\}$ of the input that makes the model valid. But what does valid mean? Let us assume an output Υ and the margin $\Delta\Upsilon\%$ existing between Υ_{sim} and Υ_{rea}, as described in Equation (4). We consider the model as *valid* when:

$\forall\Upsilon$, $\Delta\Upsilon \leq \Delta\Upsilon_{max\_valid}$ (with $\Delta\Upsilon_{max\_valid}$=*25* %.[5])

$$\Delta\Upsilon = \left[\left| \frac{\Upsilon_{sim}}{\Upsilon_{rea}} - 1 \right| * 100 \right] \% \qquad (4)$$

$[0, \Delta\Upsilon_{max}[$ is called the *interval of validity* (or `iov`).

Transition from real to simulated data

This process used the following functions (the notation '$\longleftarrow$' meaning *transfer* and ':=' meaning *affectation*):

- `alea`, with $\texttt{x}_{sim} \longleftarrow \texttt{alea}(\texttt{x}_{rea}, \texttt{k}_{alea})$ $:=\texttt{x}_{rea} \pm (\texttt{random}*(\texttt{x}_{rea}/\texttt{k}_{alea}))$, where:
  a) `random` acts to generate new random numbers (with `random` $\in$ [0, 1]), and the notation $\pm$ means:
  "if random <0.5, then '-' is chosen, else '+'"
  b) $\texttt{k}_{alea}$ is one of the variables to be determined *empirically* during the simulation.
- `btw`, for *between*, with $\texttt{x}_{sim} \longleftarrow \texttt{btw}(\texttt{a}_{rea}, \texttt{b}_{rea})$ $:=\texttt{a}_{rea} \leq \texttt{x}_{sim} \leq \texttt{b}_{rea}$
  where $\texttt{x}_{sim}$ is one of the variables to be determined *empirically* during the simulation, but unlike $\texttt{k}_{alea}$, $\texttt{x}_{sim}$ is more, at least, known as being between $\texttt{a}_{rea}$ and $\texttt{b}_{rea}$.
- `dup`, for *duplication*, with $\texttt{x}_{sim} \longleftarrow \texttt{dup}(\texttt{x}_{rea}) := \texttt{x}_{rea}$.
- `tr`, for *translation*, with $\overrightarrow{X_{sim}} \longleftarrow \texttt{tr}\ (\overrightarrow{X_{rea}})$ $:= \texttt{alea}\ (\alpha_{tr}, \texttt{k}_{tr}) * \overrightarrow{X_{rea}}$.

5 The value 25 allotted to $\Delta\Upsilon_{max}$ was chosen arbitrarily, assuming that do *rea_d* itself is not totally accurate.

Furthermore, since π_i, ρm_i, ρau_i, etc. (let them temporarily be noted generically χ_i, measured in their respective $\chi unit_i$) are given in the form of averages and measured per day, the transition from (this static form of) `rea_d` to (a more dynamic) `sim_d`, is shown in Equation (5)-a, in which δ is the *timeunit* of the simulation (with δ <1 *day*) and $\eta\delta$ is the number of δ existing in one day. The consequence is that Equation (2) also gives Equation (5)-b.

$$a)\ \delta\chi_i = \left[alea(\tfrac{\delta*\chi_i}{\eta\delta},\ k_\chi)\right]\ \ \chi unit_i/a/timeunit \qquad (5)$$
$$b)\ \delta\Upsilon_i = [\delta\pi_i * \varphi_i]\ \ Cfa/timeunit$$

Results obtained concerning the validation

Table 1 summarises a sample of the $\{\texttt{in}_{sim}\}$ we obtained. Columns 2 and 3 respectively show $\texttt{dup}(\rho m)$ and `btw` (90, 100). Column 4 and 5 respectively show $\texttt{dup}(\pi)$ and $\texttt{dup}(\varphi)$, used by Equation (5). Column 6 and 7 presents the translation $\overrightarrow{\eta_{sim}} \longleftarrow \texttt{tr}(\overrightarrow{\eta_{rea}})$, which concerns the reduction in the number of *actors* in the real society to the number of *agents* in the simulated society. Here, α_{tr} $\simeq$0.08, a choice based on our empirical knowledge of the maximum number of agents that our ADK simulator can support (in performance terms).

Table 1: Sample of the data on input side of the simulation, which validates the ASGMA model

Role	ρm %	ρau %	π kgo/h/d	φ Cfa/kgo	η_{sim} agent	η_{rea} actor
Extr.	100	97.6	20	n/a	15	171
Crush.	86	97.6	200	n/a	6	69
Grind.	89	97.6	55	9.88	22	252
Sl.wash.	99.5	40	300	3.12	4	46
Winnow.	99.5	97.6	375	1.79	2	25
Mill.grind.	68	97.6	200	11.59	1	13

Some additional $\{\texttt{in}_{sim}\}$ we obtained were:

- for all experiments, $1 \leq \texttt{k}_{alea} \leq 5$.
- the $\varsigma\varepsilon$ is `alea` (113000, $k_{\varsigma\varepsilon}$) *Cfa/month*
- the α_{cland} is `btw` (80, 90)$\simeq$*84%*.
- the δ is 5*mn* and $\eta\delta$ $\simeq$96 (i.e. 1*day* $\simeq$8*hours*).
- $\texttt{dup}(\texttt{P}_{off})$:=4500*Cfa/gAu*, $\texttt{dup}(\texttt{P}_{cland})$:=6000*Cfa/gAu*.

Figure 3 illustrates the result of the validation process. All of the simulations lasted for 720 days. Note that (i) our simulator is currently a graphical interface, which only allows the user to initialise the system and manage the simulation runs. All result analyses were handled by other, more appropriate software; (ii) in *EA*, there are 3 shafts. All of the results presented relating to *EA* actually concern the *average* of the 3 shafts. And (iii), in *TA*, we have 1 `taskzone` per role.

Observation and interpretation of the validation test

In Figure 3, the exploitation at $\texttt{time}_0$=0 coincides with the initialisation of the simulation. The actors' income is then (in

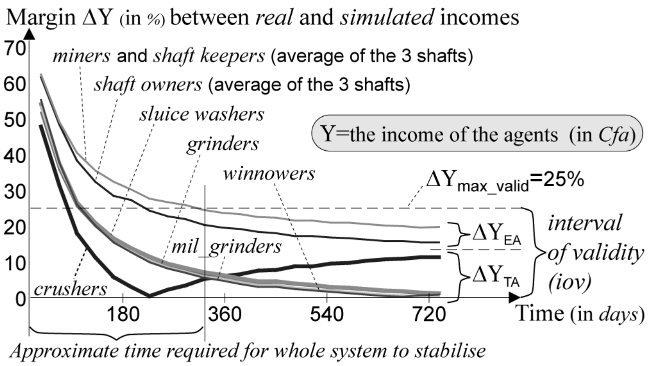

Figure 3: Illustration of the model validity through the margin between real and simulated incomes

simulation terms) still low, that is, according to Equation (4), $\Upsilon_{sim} \rightarrow 0$. Consequently, it is normal that, around $\texttt{time}_0$, $\Delta\Upsilon$ is still high. As and when the simulation advances, each $\Delta\Upsilon$ progressively converges towards `iov`. The entrance of $\Delta\Upsilon_{EA}$ in `iov` takes more times than that of $\Delta\Upsilon_{TA}$, because $\Delta\Upsilon_{EA}$ progression is slower. Indeed, unlike *TA* actors, *EA* actors have to pay "something" (remember Equation (3) before earning their real income. Still in Figure 3, it is difficult to distinguish the $\Delta\Upsilon_{\overline{TA}}$ plots because unlike *crushers* who are paid as being *oo* (thus making the plot very clear), all $\overline{TA}$ actors are paid in the same way (Equation (2)), making their $\Delta\Upsilon$ follow a similar direction of evolution. The model is fully valid beyond the *system stabilisation time*,.

Simulation objective 2: prospective research

Returning to the previously validated model, we next carried out prospective simulations related to the questions `q1` (with regard to *development*) and `q2` (with regard to *governance*) asked in the Introduction.

Problem solving steps

Concerning `q1`, the aim of the prospective research was to help decide possible values for the official gold price p_{off}, so that it would be possible to raise the Υ of *all* actors by β%. For this purpose, we first dealt with $\Upsilon_{\overline{TA}}$, by (i) raising each φ_i by β% and then (ii) using Equation (2). These operations firstly decreased all Υ_{oo}, since it should be remembered that *oo* actors pay $\overline{TA}$ actors. Thus, to raise all of the Υ_{oo} by β% too, we carried out several `tav` runs, in which we progressively increased p_{off} (by starting with that obtained by Equation (1)-a) until we approximately obtained the raised Υ_{oo} (with a margin of 5%, chosen by us).

Implicitly, the above operations actually allowed us to study `q2` at the same time. Indeed, Equation (6) (deduced from Equation (1)-a) clearly demonstrates that such an increase in p_{off} decreases α_{cland} since (i) both p_{dust} (obtained from the *initial* value of α_{cland} and p_{off}, in Equation (1)-a) and p_{cland} are constant, and (ii) $\mathsf{p}_{dust} > \mathsf{p}_{cland}$.

The best answer for `q2` is that $\mathsf{p}_{off} \geq \mathsf{p}_{cland}$, i.e. according to Equation (6), α_{cland}=0. It signifies the "death" of the clandestine channel.

$$\alpha_{cland} = \left[max\left(\frac{p_{dust} - p_{off}}{p_{cland} - p_{off}},\ 0 \right) \right] \% \qquad (6)$$

Results obtained concerning the prospective research

Figure 4 presents the possible values of p_{off} that result from our prospective research. According to these results, the authorities may, for example, take the following decision:
"if we want to raise the actors' income by 1.5% (for better development) while decreasing the part of clandestine buyers from 84% to 60% (for better governance), we should raise the official gold price up to, at least, 5500 *Cfa/gAu*".

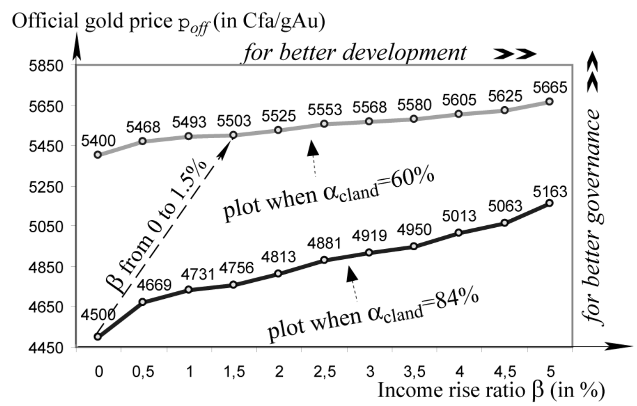

Figure 4: Results of our prospective research of official gold prices for development and governance

5. DISCUSSIONS

With regard to the generic architecture of the model

Compared to our previous research, we have improved our ADK model with the introduction of the group notion at generic level. The new resulting organisation (Figure 1) looks like the Geamas model [5]. However, Geamas, since it contains only communicative agents, does not allow a simulation of artificial situated agents and, unlike ADK, a real dynamic of the environment is quite inexistent.

With regard to the simulation

The value of $\{\texttt{in}_{sim}\}$ we obtained during the simulations is probably a solution for the validation of the model but we agree that it is not certainly unique, particularly since it depends on parameters such as $\Delta\Upsilon_{max\_valid}$. There are surely further ways to make progress in determining how far the real scope (and limitations) of the general domain of our $\{\texttt{in}_{sim}\}$ lies: by continuing the `tav` runs and by directly discussing the results with stakeholders. However, meanwhile, we believe that what we have achieved so far is promising. Technically, we have constructed a simulation mechanism that has been validated and that has allowed us to carry out initial prospective research. At term, this should lead to a tool that is as reliable as possible and which may be used as an aid for answering questions other than `q1` and `q2`.

Open discussion about natural resources modelling

In agent modelling research on the linkage between socio-economic and environmental resources management, existing models [5], [6], [7] have generally focused on agricultural or ecological resources like forests, agriculture, water, or climate. However, mineral resources also play an important role in the economic situation of the population due to the following (non-exhaustive) factors:

- unlike agricultural resources, they are at the same time exhaustible and non-renewable, leading the associated population to often migrate toward other locations after a number of years;
- as underground resources, their existence first requires prospecting. Consequently, their profitability for the population is not always warranted, unlike immediately visible and known resources;
- paradoxically, once their location has been identified, they may be a help for the population. Indeed, unlike crops, their existence is non-seasonal and they can act as alternative resources in the event of climatic disasters such as cyclones or swarm locust invasions of crops, like in some countries [3].
- *miners* and *cultivators* are often in conflict about the management of water resources while carrying out their respective activities.

Until now, only few works have considered these situations (e.g. [3]). Since the present study and our future studies will focus on mineral resources, we will certainly always consider them. However, the best idea is that researchers from diverse fields of human-environment interaction modelling combine their efforts in order to really design models that are capable of integrating and managing all of these *natural* resources.

6. CONCLUSIONS

This paper reports our work on the modelling of artisanal and small-scale gold mining of the Alga site in Burkina Faso, with the aim of proposing, via prospective research, solutions for better *development* of the actors involved, and for a better *governance* of the mineral resources, by reducing the importance of the clandestine gold buyers.

The next, forthcoming stage of this work will be to ask our colleagues back in Burkina Faso to collect `rea_d` elements that we have noted as necessary for the progress of this modelling but that are not currently at hand. For example, the spatial data required for the study of the conveyors.

Finally, we will reinforce, this time, *in conjunction with stakeholders*, the design of (i) our model, (ii) our simulation tool, and (iii) a useful methodology that can aid in the construction of social simulation models as decision-making tools. Such a participative approach is important, since it gives the modeller a better picture of the real society, with a more accurate view than that of experts/scientists. In the medium term, this will help us in integrating sustainable development indicators in this work (perhaps some of these indicators are already among the inputs/outputs data we have studied herein). For these various purposes, [8] and [9] are significant references for us.

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