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Importing participatory practices of the socio-environmental systems community to the process system engineering community: An application to supply chain

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ABSTRACT

The Process System Engineering community has an extensive knowledge and skills on supply chain design: from the time dimension (production and flow planning) to the space dimension (geographic position of facilities). Nevertheless, supply chains are also social networks where multiple stakeholders have to collaborate while they have different, and sometimes, diverging objectives. For this reason, having a more realistic model representing collaboration between the various stakeholders involved is necessary and new methods that facilitate the development of a shared representation of the system must be introduced. We propose to import a participatory method, PARDI (Problematic, Actors, Resources, Dynamics and Interactions), from the Socio-Environmental System community to the practices of the Process System Engineering community. Based on this method, we develop a participatory process in order to collect the necessary knowledge on the supply chain and its context. Following this participatory process, we then develop an Agent-Based Model as a simulation and decision making tool to support collective scenario analyses and collectively draw solutions with stakeholders. Our participatory modeling approach necessarily imposes a multi stakeholders vision (within the modeling but also in the result analyses) and therefore the search for a modeling consensus. Thus, it brings a better inclusion of social aspects in problem solving which are usually poorly considered leading to implementation failure sometimes. By comparing our approach with the classic one of the Process Systems Engineering community, we highlight the strengths and weaknesses of both and how complementary they can be. A case study on the already existing supply chain of the chestnut wood in Cévennes area (France) illustrates the capabilities of our participatory methodology. It focuses on the socio-economic model design of the first two steps (forestry activities to harvest) in the supply chain as the latter is locked because of economic and social organisation issues. The objective is to find the best action levers to unlock the resistance that forest plot owners have to remove declining wood from their land.

1. Introduction

Nowadays, the transformation of human activities towards greater sustainability requires crucial decisions with increasing urgency. Obviously, this question challenges researchers who need to develop new methods and tools to help decision makers, but also to provide them with new scientific information. In such perspective, acting on supply chains can be an efficient lever for action because they are the skeleton of our society. Indeed, they structure how financial, physical and information fluxes are exchanged. These networks composed of nodes and links, need to be organized both in space and time dimension to ensure sustainability (Barbosa-Povoa and Pinto, 2020).

In order for supply chains' research to contribute to society transformation, two aspects are decisive to take into consideration. First, in the real world, the supply chain design contributes to organize industries from the geographical, political, social, environmental and economic perspectives. All these aspects form a complex intertwined-issues system, which makes the decision making process challenging (Roth et al., 2017). Therefore, researchers need to build methodologies and tools helping to foresee decisions consequences in order to find the most appropriate ones. To build such methods and tools is not the biggest challenge, but to make the outcomes meaningful and relevant for decision makers is where

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the key is Bennett et al. (2013), Parker et al. (2002). Indeed, taking care of the practical use is of utmost importance for research production if society transformation is the target. In the perspective of supply chain design, economic viability is the most obvious objective and environmental protection is often considered as a second level objective. Second, supply chain is also a matter of social organisation. Indeed, they are multi actors systems by nature, with each actor owning some infrastructures of the whole supply chain and having their own objective. These actors can have considerations that are sometimes subtle, not much visible and conscious because they are deeply embedded in their practices or they reflect their identity in terms of culture and values. These hidden objectives have an influence on decisions (Voinov et al., 2016; Voinov and Bousquet, 2010), so when designing supply chains taking into account the social aspects is of utmost importance in the decision making process.

Researchers from the Socio-Environmental System (SES) scientific community have developed participatory methods, such as the PARDI method, to solve problems of conflicting use of natural resources or resource management for environmental impact reduction (Etienne, 2014; Simon and Etienne, 2010). In this paper, to help supply chains' research contribute to society transformation by taking into account the two decisive aspects previously identified, we propose to describe existing approaches in the SES community and import some practices to the Process System Engineering (PSE) community. The goal is to build simulation models relying on a collaborative decision making process for the management of natural resources. The novelty of the methodology is to stimulate the participation of stakeholders in the co-construction of a simulation model and in the development of management scenarios. The progressive shift from supply chain management based on a centered or rationalist approach towards a collaborative approach (decentralized) needs the emergence of new tools that focus on co-construction of models and the sharing of information but also by including an understanding of the particular context of the studied system that is to be managed.

The remainder of the article is structured as follows. In the following section we give a literature overview of existing attempts in multi objectives and multi stakeholders supply chain. Then, in Section 3 we detail our methodology and we apply it to the case study of chestnut wood valorisation in the Cévennes area (France) in Section 4. The objective of the case study is to determine the best action levers to unlock the already existing local chestnut supply chain. Finally, we draw conclusion and give some future research perspectives in Section 5.

2. Literature overview

Supply chains are extensively studied in literature by the Process Systems Engineering (PSE) community. Commonly, the community explores two dimensions: time and space, as described in Barbosa-Povoa and Pinto (2020).

On the one hand, regarding the time dimension, the main challenge is to plan decisions and flows to enhance productivity, reduce costs and sometimes environmental impacts. For instance, Attia et al. (2019) propose a linear programming (LP) model to plan tactical decisions related to an oil and gas supply chain. The model is solved with a multi objectives approach: minimizing CO_2 released, costs, natural resources depletion rate and maximizing revenue in order to determine which strategy to adopt regarding production of oil and gas. The case study shows that according to the price and penalty conditions it is preferable to produce oil domestically and buy gas on the international market. Ehrenstein et al. (2019) include stochastic models to plan flows in petrochemical industry and cover uncertain disruptions like extreme events. As for Guarnaschelli et al. (2020), authors propose a two-stage stochastic mixed integer linear programming model to plan production and distribution over dairy supply chains.

On the other hand, the space dimension explores how supply chain must be geographically structure to ensure optimal performance. Mixed integer linear programming (MILP) models are the most widespread because of the nature of the problems to solve, including or not multi objective approaches (Patel and Swartz, 2019; Rabbani et al., 2020; Yavari and Zaker, 2020). Some papers cover uncertainties with stochastic models such as Saif et al. (2019) where the optimization of a municipality solid waste supply chain under price uncertainty was addressed using a two stages stochastic MILP model.

The assessment of the supply chain should consider the different pillars of the sustainability because decision makers and/or stakeholders should be informed of a wide spectrum of impacts. In current research studies, attention is more focused on the techno-economic and environmental aspects, often combined. In addition to these two dimensions, the social aspect of supply chain is more and more considered because it is crucial but it is more difficult to assess. Bubicz et al. (2019) review 621 articles to extract the trends and gaps when incorporating social aspects in sustainable supply chains. Authors identify that researchers are struggling to describe relationships between the three pillars of sustainability and especially with the social aspect as there is no consensus on how to identify, control and measure social sustainability. For instance, jobs creation (Miret et al., 2016; Santibañez-Aguilar et al., 2014; You et al., 2012) and social welfare are by far the most frequently measured social aspects but the main pathway is to consider actors through their economic interest. As a result, the social assessments are still significantly less elaborated compared to the environmental or economic ones. For the PSE community, the difficulties with social assessment are due to the lack of theoretical underpinning, the complexity of social indicators, their subjective and qualitative nature, and a lack of data. Irrevocably, it is vital to devote more research to the quantification of social aspects, to the selection of meaningful social indicators, as well as to appropriate modeling approaches (Messmann et al., 2020). The major contribution of this article concerns this last point.

Another important challenge in managing supply chain is the development of decision making models that can accommodate multi stakeholders who may be in charge of different activities, and sometimes with conflicting interests. While most of the approaches propose a centralized view of the supply chain (full control of all the activities by one entity), some studies start to include a decentralized view where different stakeholders must collaborate. As a result, new approaches have to be created to represent this more realistic situation. Some papers promote cooperation between actors, Ng et al. (2013) develop a fuzzy logic optimization for the design of network configuration of a multi owners palm oil processing complex. Each actors' profit-oriented goal is modeled to consider their willing to play a role in the industrial symbiosis under study. Another approach developed by Andiappan et al. (2019), is to use cooperative game theory analysis to determine the optimal profit from which palm oil eco-industrial park stakeholders will be convinced to invest in green technologies. On the other hand, other researchers take the opposite stance by considering non-cooperation between actors. Here, supply chains' actors play in their own economic interest without any consideration about other actors (Cobo et al., 2020; Nicoletti and You, 2020). In these multi actors approaches, the social dimension can be included by considering how social interactions can influence some variables of the supply chains. Especially, Singh et al. (2014) develop an Agent-Based Model (ABM) in order to reproduce the social interactions between actors of the corn sector. Actors are participating into a double auction process, which determine the corn price. Then, a genetic algorithm is used to solve a mixed integer non linear pro-

gramming (MINLP) model for the design of bio refinery supply chain networks under the ABM corn price output.

The above discussion mentions papers that include the social dimension into supply chain studies by modeling stakeholders' interactions. However, the modeling process itself is also a space for social dimension inclusion. For instance, Heintz et al. (2014) develop a methodology involving stakeholders from all the hierarchical stages (strategic, tactic or operational) of a chemical company, in the modeling of sustainable chemical products. Customers' preferences and designers' opinion are collected and written as statements with unambiguous languages (Semantics of Business Vocabulary and Rules (SBVR) and Object Constraint Language (OCL)). Then, these statements are used to build the requirements tree of the chemical product. In other domains, especially in Socio-Environmental Systems Science (SES), the modeling process is sometimes more important than the model itself. Especially, a community of practice called ComMod has defined a charter to explain their scientific posture (Barreteau, 2003). The main principle is to consider that actors of application fields are the experts, meaning that researchers are no more problem solvers but solution catalysts. In this respect, participative modeling methodologies are used to help decision making. By gathering various real world actors and making them model their SES, researchers create discussion arena for trade-offs and decision triggers. Several tools can be employed to catalyse discussions: especially, role playing game (RPG) (Moreau et al., 2019) and semi-structured interviews (Papazian et al., 2017) are used to make collective and individual knowledge emerge through interactions created inside the simulation space (the serious game). Researchers have to collect this knowledge and structure it into models to help solving stakeholder's problem. Another approach completely integrates stakeholders into the modeling process, i.e. PARDI method (Problematic, Actors, Resources, Dynamics, Interactions) (Etienne et al., 2011). In the PARDI method, stakeholders are participating in five brainstorming workshops corresponding to the successive themes mentioned in the acronym: first they discuss the Problematic under study, then they list Actors and Resources of the system, thirdly they describe the Dynamics of the system and finally they build a diagram describing how actors Interact between them and with resources. This diagram is then the conceptual model upon which researchers rely to build decision making tools (ABM, RPG, or another one).

Garcia and You (2015) have clearly stated the three challenges of supply chain design:

- multi scaled: coordination of multiple spatial and temporal scales.
- multi objectives: definition of what is the most important to assess the consistency of solution proposed and how to find trade-off between antagonist objectives.
- multi players: decentralized decision-making bring modeling and computing issues.

These three challenges are intrinsically linked to the social dimension, because as there are multi actors it is very likely that there are multiple objectives and scales. Therefore, taking into account the multi actors character in the supply chains design is of utmost interest. Computer based solutions, mainly supported by game theory, are often proposed to tackle this problem. Nevertheless, these approaches are limited because researchers have to master actors' objectives with perfection if they hope to find a relevant trade-off. In practice, sensibility analyses are driven prior to problem formulation but there is no guarantee that the formulated problem will be in accordance with the real actors requirements. The ComMod approach is based on both computer modeling and social simulation of the solution proposed during RPG or collective scenario analyses. In addition, the problem formulation is proposed directly by the actors of the system under study. Thus, it ensures more flexibility in terms of actors' objectives definition and problem formulation.

The main conclusion of this literature overview is that social issues are often technically complex and their resolution needs the collaboration between multi stakeholders with different and sometimes diverging objectives. For example, in a supply chain, stakeholders encompass public authorities, private companies, end users, scientific experts, social interest groups, among others. In order to have a more realistic model that represents the collaboration, new methods that facilitate the development of a shared representation of the system must be proposed. This way to construct collectively models improves the modeling and produces better results due to the mixing of very different knowledge and skills. These recent participatory methods would provide new relevant ways to include social issues in PSE models.

In this paper, we import the PARDI method into the PSE domain in order to include the social dimension in the modeling process stage to fill this gap identified in the PSE literature. Especially, we develop, collectively with stakeholders, an ABM for decision support in the chestnut wood valorisation sector for the local economy of Cévennes area (France). Thus, the social dimension of the supply chain is included both in the modeling process because of its participative nature, and in the model itself with the ABM. Classically, when designing a supply chain, PSE researchers build models based on a superstructure they have initially constructed. Then, they run calculations and analyse results. Nevertheless, results are based on the strong hypothesis that actors will behave exactly as initially established, but in fact, the reality can be very different. Therefore, modeling with stakeholders from the very beginning to results analyses is of utmost importance in order to satisfy their requirements, to ensure the relevance and the control of the study, and to guarantee meaningful and relevant results. Therefore, we advocate that participative modeling processes are likely to be the key to consider the social aspects in PSE models as described in the introduction.

3. Methodology

The success of participatory modeling depends on three key choices that are made and the way the process is driven: which stakeholders to involve, how and when to involve them. In this section, we will introduce the four-step methodology we developed for our participative modeling process (Fig. 1) and how it helps to make the three-abovementioned choices. This formal procedure is used to systematically elicit a representation of the system and to avoid premature discussion in the model construction. The method relies on an open and dynamic management approach, capable of anticipation and adaptation. The methodology encourages participants to describe their individual vision of the system but also to express individual knowledge that then leads to the emergence of collective knowledge.

The four steps are chronological and cannot be executed in another order because outputs of one step correspond to the inputs to the next step. For example, we cannot reach a common representation and perform co-modeling if we have not previously invited stakeholders concerned with the key question and identified their management entities, the resources used, and the main processes that occur in the studied system. Prior to that, there is a preliminary step dedicated to context analysis where system boundaries, issues and relevant stakeholders must be identified. During this phase, information and data on the system are collected. As there are no specific methods for such investigation, we will not be talking about that in this paper, but it is an unavoidable milestone to identify and describe the context.

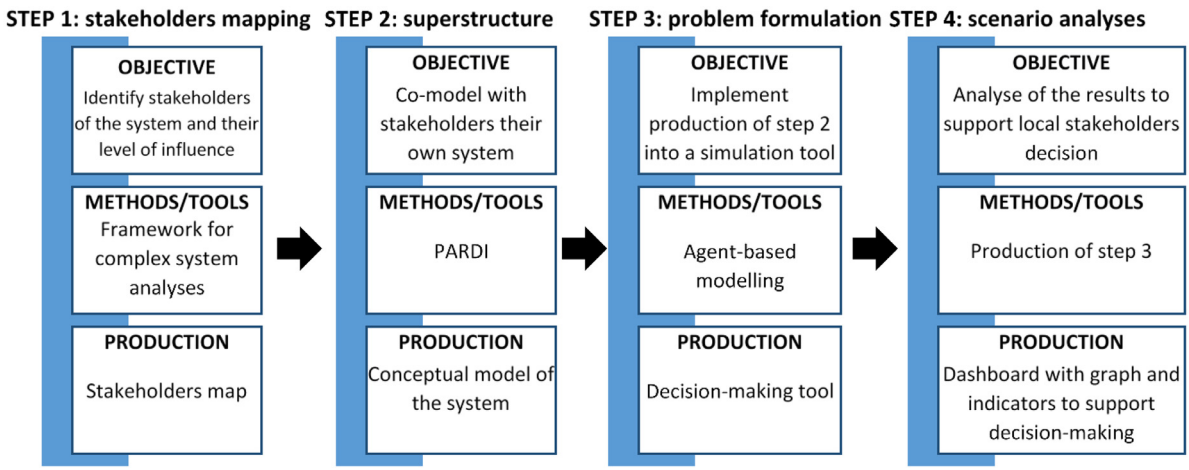

Fig. 1. Participative modeling methodology.

3.1. Step 1: stakeholders mapping

The main objective of this step is to identify stakeholders of the system and their level of influence on it. In reality, persons or institutions embody stakeholders, but here we are talking about roles and not persons. Thus, two stakeholders can correspond to only one physical person or institution and two different roles are assigned to one person. Mapping the stakeholders is then important to know who we are going to consider and for which role.

In this respect, a methodology proposed in a previous work, Roth et al. (2017) can be used. The paper proposes a framework aiming to de-intertwined decision context by classifying scales, issues and stakeholders over four levels:

- internal level – items that have direct relation and/or influence on the object of study,
- meso level – items that remain close to the object of study but with more abstraction,
- macro level – items that have a diffuse influence on the object of study,
- external level – items that are exogenous but have a punctual influence on the object of study.

Roth et al. (2017) explain also that stakeholders' objectives must be identified in order to understand their roles and actions on the system. Therefore, stakeholders should be labelled with their objective(s) and their belonging level(s) on the stakeholders mapping. Then, we need to choose among them who will be included in the participative modeling process. For this, a possibility is to specify the links that exist between the identified stakeholders and to clarify this relationship. As a result, gaps can be identified or it is possible to point out stakeholders who have no relation with any others. Indeed, some stakeholders could have been listed in first-line but appear to have no relevant links with others for the case under study. In this case, these stakeholders could be withdrawn of the diagram. Sometimes, the choice must be done in intelligence with previous field research works and context analyses and depends on the situation:

- Stakeholders that are not reachable - Some stakeholders are known to be not reachable, especially those of the macro level that are too far from the object of study and would not participate because a lack of direct interest and/or time.
- Stakeholders with radically oppozed points of view - In case of conflicting situations, it is sometimes preferable to remove some stakeholders at the beginning of the process and include them later to prevent mutually exclusive requirements due to radically oppozed points of view. If such case is identified, researchers have to define a strategy to deal with that, because if they do not they will be likely to face very long and sterile debates, monopolized by the two stakeholders with radically oppozed points of view, driving others to lose interest in the project. Nevertheless, for the sake of transparency, and to prevent bias in the study, confrontation of the radically oppozed points of view is needed. Two strategies are then possible:
  - (1) Remove one of the stakeholders with radically oppozed points of view (the one that you feel most appropriate) at the beginning of the process and invite him/her latter in the process to ensure transparency and let the debate open.
  - (2) Define two groups of stakeholders with the radically oppozed points of view split in the two groups, perform the process with the two groups in parallel and confront the outputs at the end in a plenary session.

In both cases, researchers will obtain the matter to work while keeping the debates open.

There is no specific rule for the ideal number of stakeholders to invite for the second step of the participatory process. Nevertheless, the more stakeholders are invited the more difficult it will be to manage for the group animator (meaning researchers). On the contrary, the less stakeholders are invited the more biases the outputs of the process will have. This is why the stakeholders map is necessary, as it gives an overview of the potential categories of stakeholders to invite in the participatory process. Ideally, the selection of one person by category will ensure a good diversity but, as explain before, it can represent too many people which is difficult to manage during the workshops. The researchers thus have to estimate the number of persons they think they can manage. As an indication, we advise that around ten actors is suitable to ensure diversity while remaining manageable for the group animator.

The output of this step is a stakeholders' map that facilitate the identification of social networks and a better understanding of individual mental models to promote all the dimensions of the sustainable development. In addition, the stakeholders' map will provide an holistic view on the system, which is mandatory to select participants of the participatory process with full knowledge of the facts.

3.2. Step 2: superstructure

After the stakeholder mapping and choice, comes the participative modeling process in itself with the objective to co-model together with the stakeholders their own system. As explain in the

literature overview, there are several methods for this step. We have chosen the PARDI method because the translation into ABM of its resulting co-model is more straightforward than with others. As we will see later in this section, agents, objects and concepts that need to be implemented into ABM are clearly described once all the steps of the PARDI method are achieved.

PARDI is the acronym of: Problematic, Actors, Resources, Dynamics and Interactions that identify the five steps the method uses to elicit stakeholder mental models of the system under study. Thus, it allows the progressive emergence of a shared representation of the components and dynamics of the system. Workshops with the stakeholders chosen in the previous step to be included in the participative modeling process (i.e. key stakeholders), are organized to cover each successive steps mentioned in the acronym:

- Problematic: researchers have to initiate an open discussion over the sustainability issues they are facing. During this phase, a richness of qualitative information will emerge from the discussion and researchers have to collect it live because they are fundamental to understand field reality. At the end of the workshop, researchers must guide stakeholders to formulate a key question to treat, gathering all their individual interests.
- Actors: here it is a brainstorming session where stakeholders must list actors related to the question they previously have formulated. Similar to stakeholders, when talking about actors, we are talking about roles. Actors can be a direct actor (representing himself/herself) or an indirect one (representing a bigger entity like public institution for instance).
- Resources: in a brainstorming session, stakeholders list the relevant resources (for instance wood, water, power plant…) of the territory according to the retained actors and related to the problematic situation. The main characteristics of the resources can also be added. For each resource, the indicator that seems to be the most relevant for the decisions regarding that resource can be debated. These indicators will be used in the model or during the scenarios assessment to compare stakeholders' points of view. Exogenous resources can be considered if they have critical influence on the system (biomass seasonality or favorable year, for example).
- Dynamics: stakeholders are asked to describe spontaneous and natural dynamics related to the problematic. It consists of listing the main processes that drive changes in the territory in relation to ecological dynamics, economic dynamics, or social dynamics. For instance, in chestnut wood valorisation, the natural dynamics of chestnut growth are essential to be described. To deal with such dynamics, stakeholders may agree on the successive states taken by the resources or processes and specify the causes that generate the transition from one state to another, including the time required. The main gap that can appear is that no stakeholder possesses enough knowledge about an identified process or resource. The group must call upon an expert.
- Interactions: finally, stakeholders have to create a diagram to model interactions between actors and resources, by stressing how actors interact with others and use resources. It is a pivotal step since it leads to the conceptual model that represents all interactions related to the key question. As an illustration, a generic version of this kind of diagram is depicted in Fig. 2.

Actors and Resources are visually differentiated and arrows link them. Each new arrow is labeled with action verb in order to describe further the type of interaction. This interaction step is generally the richest of the co-modeling process because it is essential to keep a record of all the previous steps of the PARDI method. It is a real added value to capture why and how a particular actor, resource, or interaction was mentioned, retained, eliminated,

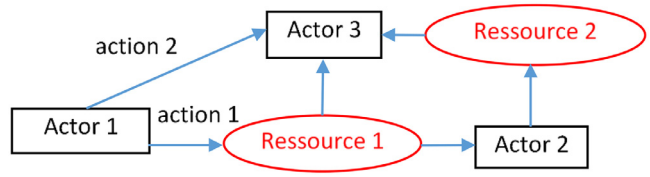

Fig. 2. Generic interaction diagram.

or transformed. When finished, this kind of diagram constitutes the conceptual model of the ABM to be developed.

PARDI method appears to be an incremental process driving stakeholders toward the final model of Fig. 2. The role of modellers is very important here as they are the translators from what stakeholders say into the interaction diagram at the end of the PARDI method. It is very likely that the stakeholders are not used to modeling, therefore they will not directly build the interaction diagram on their own. Stakeholders will interact and modellers have to extract from the discussions the key concepts and propose to add them on the under-construction interaction diagram. They ask the stakeholders to validate or not the proposition. In short, modellers have to guide stakeholders to make the back and forth from their reality and the model, as they will not do that naturally. Indeed, it is likely that modellers add bias in the process but the validation of stakeholders is always asked in order to compensate that.

The main output of this step is a conceptual model of the system under study.

3.3. Step 3: problem formulation

Here the objective is to translate the conceptual model of Step 2 into a simulation model.

As explained above, qualitative information and diagrams issued from PARDI method are the basis of the ABM development, which make the ABM tool particularly suitable. Especially, the PARDI step defines the superstructure of the problem and Step 3 is where the complete formulation of the problem is done with parameters, variables, equations and constraints definition. The details on the construction of our ABM will be given in Section 4.4.

The main output of this step is a decision making tool.

3.4. Step 4: scenario analyses

When ABM is functional, the last objective is to analyse the results to support local stakeholders' decision. In this respect, another workshop is organized in order to present the model and collect stakeholder' s feedbacks on it (model corrections are likely to be necessary). When the model is validated, open discussions are settled to decide which scenario stakeholders and academics want to explore with ABM. If possible, scenarios can be run live. Sometimes, it is preferable that researchers withdraw to make the necessary analyses and come back for another workshop to present final results.

The main output here is a dashboard with graph and indicators to support decision-making.

3.5. Discussion

Fig. 3 presents the two approaches for the modeling of systems. Both start with a detailed analysis of the system, its environment and its context.

Often, when studying a system with multi actors, decisions related to the management of this system are divided into different levels, e.g. strategic, tactical and operational. The approaches developed in PSE community offer the possibility to deal with only

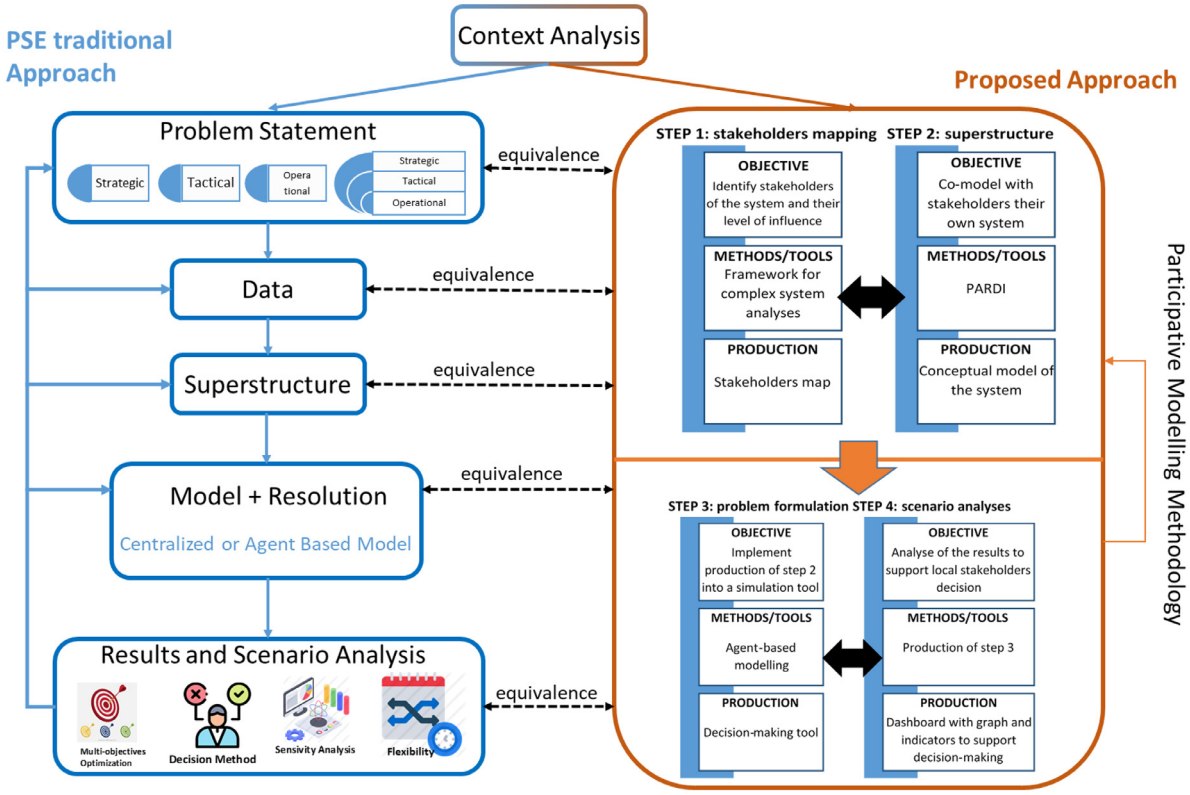

Fig. 3. Comparison between PSE approach and the proposed approach.

one of these levels or with several of them (two or all). In the latter case, the levels are considered either with a sequential approach (the outputs of one level correspond to the inputs of the next level) or with a simultaneous approach (global resolution of all levels). On the other hand, due to its construction, the proposed approach is structurally focused on the consideration of all the levels through a simultaneous approach.

The second major difference between the two approaches concerns the collection of data and knowledge, which are organized in very different ways. In the PSE traditional approach, they are mostly collected from a limited number of people and experts or even from a single entity when the whole system is managed centrally. In contrast, participatory modeling necessarily imposes a multi stakeholders vision and therefore the search for a modeling consensus. Moreover, with this approach, the scope is broader because, in addition to the stakeholders directly impacted by the project, it also considers indirect actors. This broadening of the system boundaries thus makes it possible to incorporate directly into the model all the dimensions of the sustainability through social, economic, environmental and political actors.

The last major difference that can be noticed is that our proposition includes sustainability, but it breaks with the classical mathematical approaches in PSE. What PSE researchers are doing usually, is to optimize solutions with economic objectives under social and environmental constraints expressed as mathematical constraints (or with multi-objective approach but it is still mathematics). In our proposition, social and environmental constraints are not written in models with mathematics but they exist at the modeling process level. Indeed, as the modeling process is participatory, each actors can bring its points of view, thus objective, to the model. For instance, an agent of a National Park will bring an environmental objective while a mayor is more likely to bring societal considerations. Therefore, sustainability is taken in consideration prior to the decision (a priori) so the result is directly the compromise.

The two approaches are not to be contrasted but can be complementary. Indeed, some specific steps of the participative modeling methodology could be used to collect information or knowledge useful for the first three phases of the traditional approach (dashed arrows). Conversely, the data and knowledge from the latter could be used to fuel discussions among stakeholders and thus avoid starting from scratch.

The last two steps of the traditional process are critical as it influences the decision making. However, different feedback loops depending on the approach are possible in order to obtain a solution that satisfies all the actors. The advantage of the traditional approach is that it is possible to quickly go back on targeted steps of the modeling process to question certain hypotheses, constraints, objectives and data. For the proposed approach, as shown on Fig. 3, interactions between Steps 1 and 2 on the one hand, and Steps 3 and 4 on the other hand are possible. However, once in the problem formulation and result analyses started, it is much more difficult to go back to the superstructure co-construction as it requires to gather all the stakeholders to find a new consensus following major modifications. This can be a tremendous and time-consuming task but it still possible.

4. Case study: chestnut wood valorisation in Cévennes area (France)

The Cévennes area is a South French mountainous and forest area. It straddles two administrative districts: Gard and Lozère. Historically the chestnut tree is the symbol for native inhabitants who are strongly emotionally attached to it. Currently, local economy relies on chestnut tree whether it be for the wood (timber, wood fuel, furniture…) or the fruit. However, due to traditional activities decline, climate change and pests attacks, the

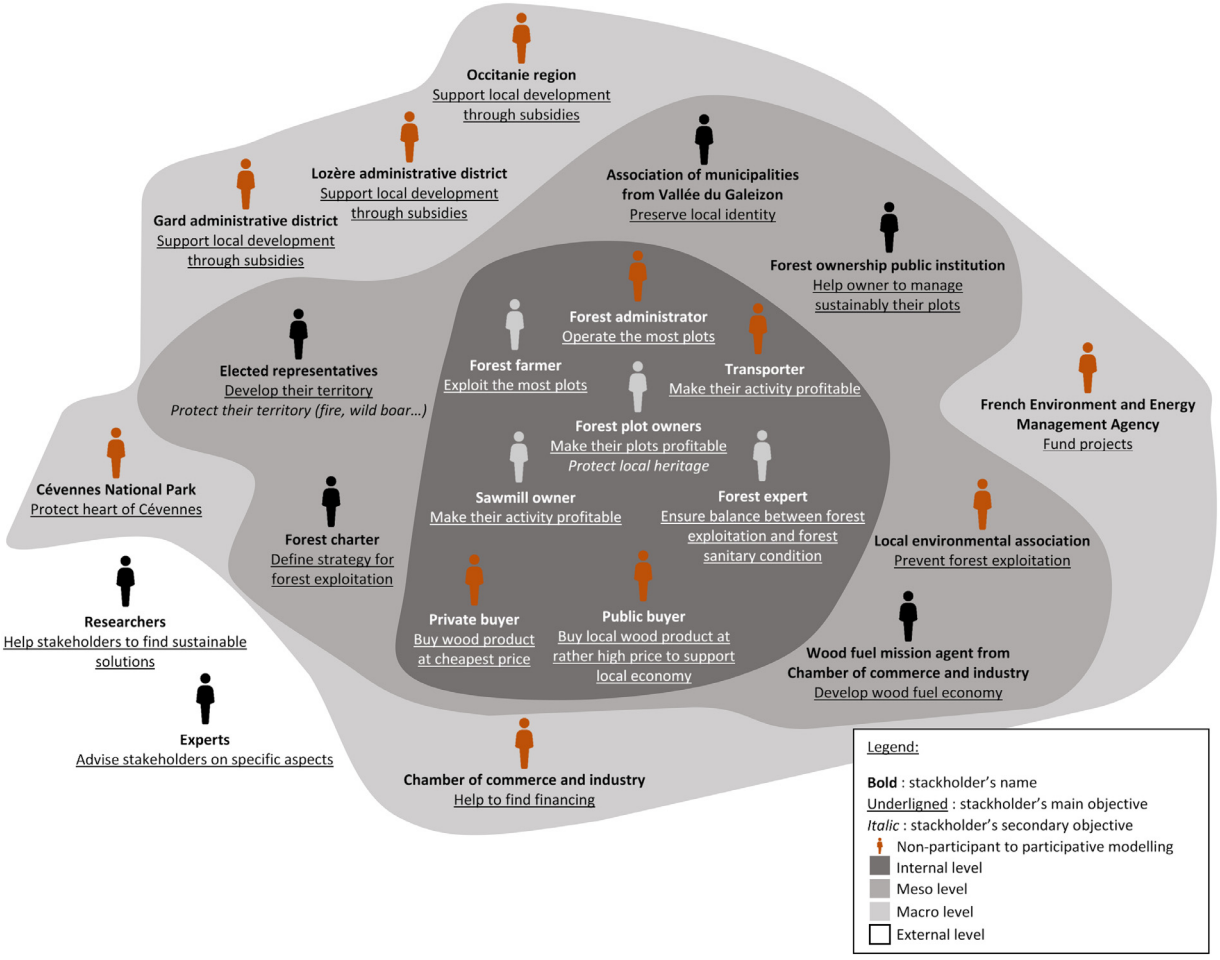

Fig. 4. Stakeholders map for chestnut wood valorisation in Cévennes area.

chestnut grove is in poor sanitary condition and in a quasi-neglect state. Thus, multiple dangers arise: fire risk, wild boar population increase, Cévennes identity loss, landscape degradation grow… Therefore, some local stakeholders (forest plot owners, forest loggers, sawmill owners, local administration agents, elected representatives and scientists) have decided to gather their efforts toward solving the problem and find a sustainable organisation for the local chestnut wood supply chain. In this context, the transformation of wood into valuable products (or else) is not the main issue but the organisation of the system, from the wood harvesting to the transformation point, is where the challenge lies. Therefore, in this study, we will focus on the first part of the supply chain, meaning every step before the transformation step: forest plot owners and forest rangers negotiations, harvesting and transport from the forest toward transformation points. Every step after (transformation and commercialisation) will be considered only by the economic value of the products.

4.1. Step 1: stakeholders mapping

Fig. 4 shows our stakeholders map build thanks to previous field works (mainly interviews). As explained in the previous section, stakeholders were distributed over the internal, meso, macro and external levels (see Section 3 – Step 1). On this map, stakeholder's objective (primary and secondary if necessary) are specified. The stakeholders in orange/red are not invited to participate to the modeling process:

- Transporter: The voice of this stakeholder can be supported by stakeholders that work with them like harvester for instance,
- Public buyer and Private buyer: These two stakeholders are the last link of the supply chain and finding outlet for the transformed chestnut wood is not the purpose of this study
- Forest administrator: Forest farmers, Forest plot owners and Forest ownership public institution can represent the point of view of this stakeholder.

At the meso level, local environmental associations were not invited because they are not very active in Cévennes even though they exist. No actors from the macro level participate to the modeling process. Here, the identified stakeholders are all backers. The mainstream way to reach them is to answer to call for projects and the backers select the best projects according to their politics. It would be very interesting to include people who define backers politics as participants but unfortunately they were not reachable because they have too high position in the pyramidal hierarchy and they lack direct interest.

4.2. Step 2: superstructure

During our participative modeling process, three workshops were organized for the PARDI method. As explained in Section 3, the objective was to mash up knowledge to collectively converge towards a shared model where every stakeholders' point of view meets. In practice, the time schedule of workshops needs to be organized in concertation with stakeholders to guarantee that the

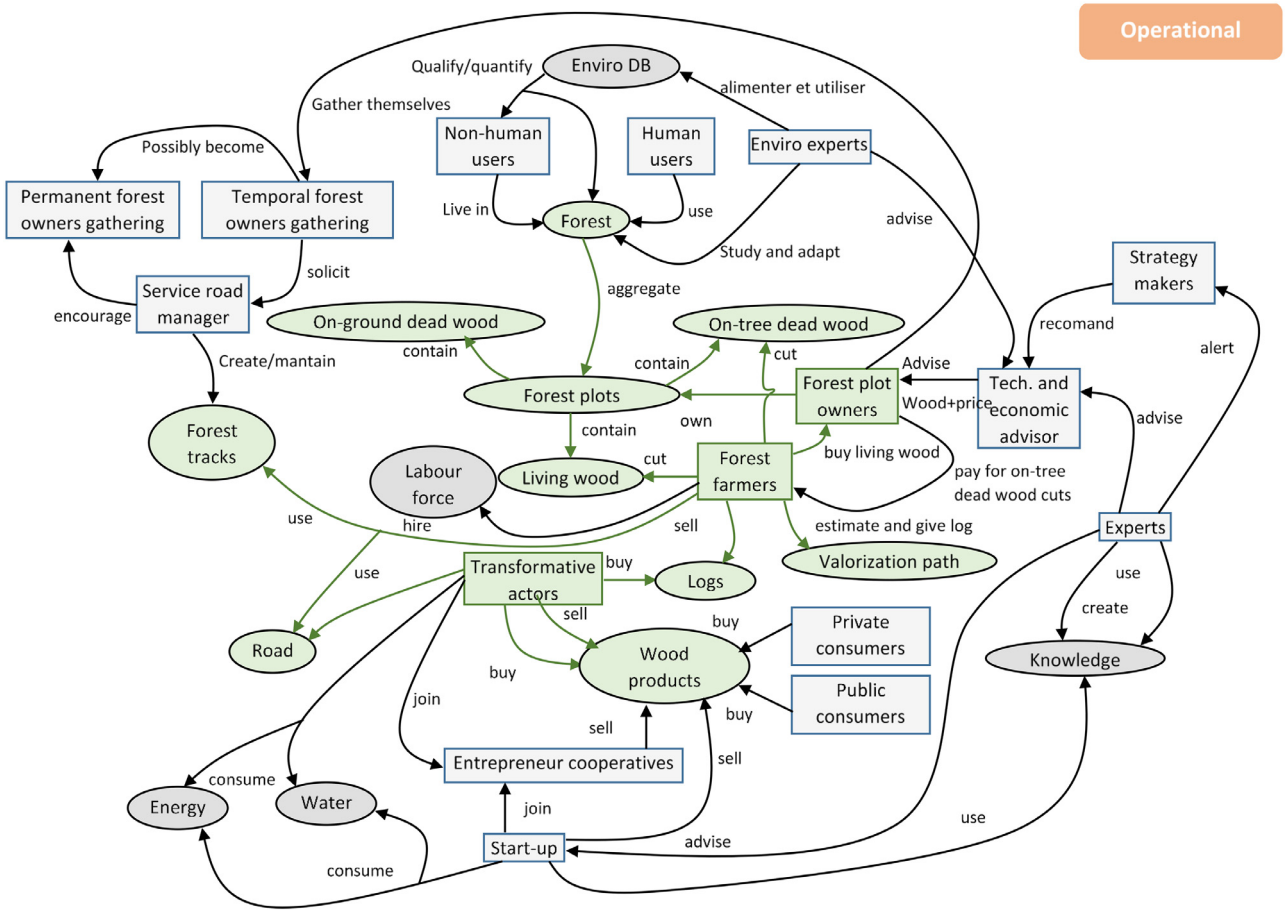

Fig. 5. Interactions diagram at operational level for the chestnut wood valorisation in Cévennes area.

modeling process would not bore them and prevent cancellations. The schedule of our workshops was as follow:

- half a day for problematic formulation
- a whole day for actors, resources and dynamics listing
- half a day for interactions diagram construction

During the first workshop, the deep and rich discussions covered every dimension of the project: technical, environmental, economy, social and political (local and wider). The main message was that there is an urgent need to remove dead wood from forest and make chestnut durable where it is adapted, but at the same time to remove it from area where other species are more suitable. It seems that there is no technical obstacle to reach this goal but the problem comes from the economic aspects: high investments are needed but no one can or want to pay for it. In reality, it is a question of political strategy. There are other sectors more economically attractive for backers but stakeholders have to make regional and national politics evolve toward more balance between economy and other aspects (environment, local identity preservation…). In that perspective, the social aspect is crucial. Indeed, if the actors come together they can put pressure on politics. Nevertheless, to achieve such uprising is not easy and fast. Local politics have to play a crucial role of communication either on tradition and Cévennes identity (but by experience it is not enough) or on fire risk (which is much more efficient due to the fear it triggers). At the end of the discussion the formulated question was:

"How to federate Cévennes' actors to set up action in order to remove declining chestnut and prepare tomorrow forest?"

After the four first steps of the PARDI method, interactions diagram of Figs. 5 and 6 were produced. Fig. 5 describes the functioning of Cévennes wood system at operational level, meaning the existing local wood supply chain. In Cévennes, the main difficulty is forest exploitation. Two aspects such as plots accessibility and road capacity restrictions are the main reasons why exploitation costs jeopardize the profitability of forest exploitation. Thus, the existing supply chain is completely stopped and needs to be reactivated through new levers of action. Fig. 6 describes the system structure in terms of strategy and tactic definition. Indeed, in order to make operational level evolution toward supply chain reactivation projects need to be set up. Such projects need funds to be achieved so the project manager needs to convince backers. For that, population awareness can be activated in order to put pressure on backer politics makers and convince them to fund projects.

4.3. Step 3: problem formulation

As explained in the Section 3, Interaction diagrams of Figs. 5 and 6 are the foundations for ABM. Fig. 5 shows only the elements that can be relevant in ABM. Indeed, what will be interesting is to model the existing supply chain of Fig. 5 and through constraint removal (more plots accessible, price policy, forest strategy…) to simulate effects on the forest and the local wood economy. Therefore, in this section we will only focus on Fig. 5 but we will come back to Fig. 6 in the conclusion (Section 5). The ABM is implemented using the CORMAS platform (Bommel et al., 2015) which is an agent based model development platform, developed by a CIRAD (The French agricultural research and international cooperation organization) team.

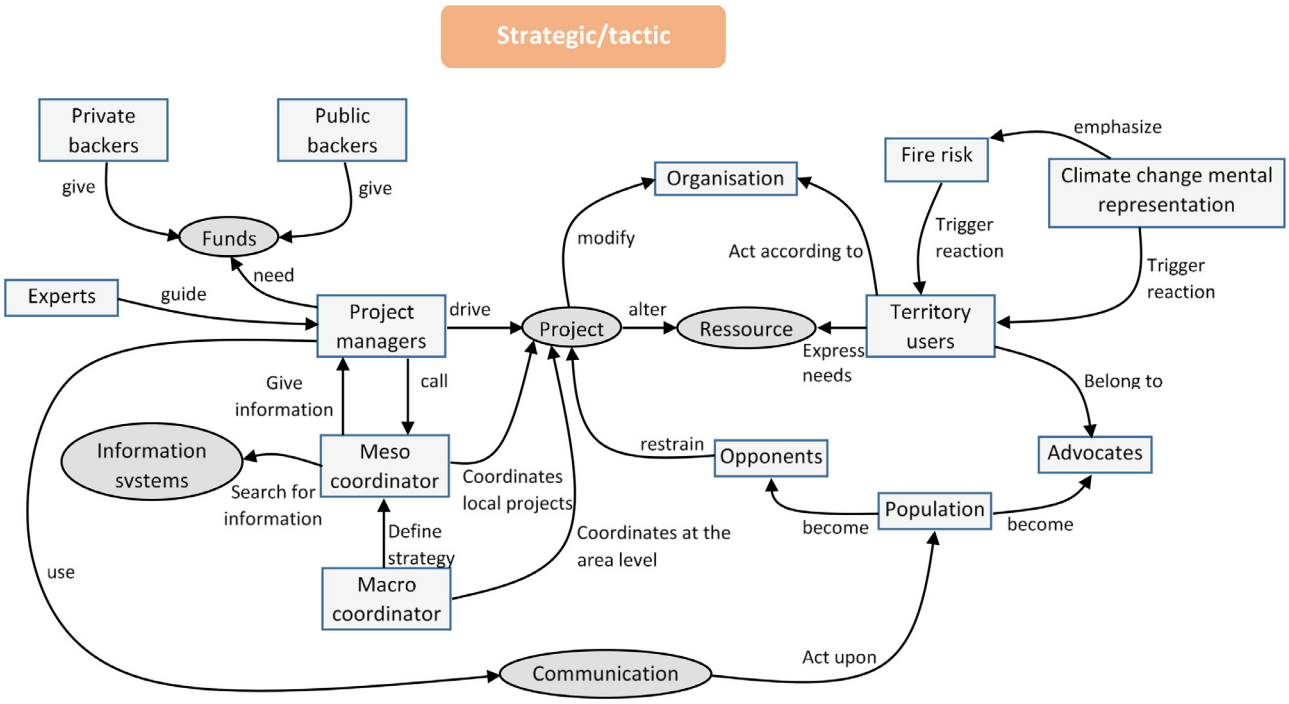

Fig. 6. Interactions diagram at strategic and tactic level for the chestnut wood valorisation in Cévennes area .

On Fig. 5, the existing supply chain is compozed of the elements in green and this is the heart of our ABM. Fig. 7 shows the class diagram of our ABM.

Objects in green are geographical objects, objects in red are agents and objects in blue are passive located objects. The geographical unit element is the “Pixel” which as a fixed unit surface. “Accesses” (“Roads” and “Forest pathways”) aggregate “Pixels” and have a maximum capacity. For instance, a truck of 19 Tons cannot run on an “Access” which has a maximum capacity of 12 Tons. “Parcels” also aggregate “Pixels” and the sum of the pixel’s unit surface is equal to the area of the “Parcel”. “Parcels” are described with several attributes:

- the wood quantity on the parcel,
- three rates that give the proportion of energy wood, service wood (eg. Pole) and lumber available on the parcel,
- three difficulty indexes, the operation difficulty index represents how operations on the parcel are difficult (obstacles, important slope etc.), the logistic index represents how difficult it is to transport machines and wood from or toward the parcel, and the access quality index represents how the access toward the trees inside the parcel are maintained or not.

Each “Pixel” belonging to a “Parcel” has a “Tree” as occupant. “Trees” are qualified thanks to their age and the proportion of dead wood on it. “Owners” own one or more than one “Parcel”. Some of the “Owners” are volunteers others are not. « Owners » are considered as volunteers when the accept that their “Parcels” can be harvested. Those, who are considered not volunteers do not take care of their “Parcels” and sometimes do not know they own such “Parcels”. An “Owners” that is a volunteer manifests his/her wishes to have their “Parcels” harvested by ask “Forest ranger” (a person interested in buying the wood on the “Parcels”) to give a quote to these “Parcels”. “Forest ranger” identifies the neighborhood of the asking “Owner”, estimates the group of “Parcels” (the parcel of the asking “Owner” plus the parcels of the neighbors) and gives a price to the “Owners”. If the price is high enough, meaning that the “Owner” gain is better than its lower band attributes, the “Owner” accepts the price but if not the “Owner” rejects the price. In the case that, every “Owner” rejects the price the “Forest ranger” gives up the site, while if at least one “Owner” accepts the price the “Forest ranger” re-estimates the groups of “Parcels” (without those whose “Owner” rejects the price) until every “Owner” accepts the price. When the “Forest ranger” estimates “Parcels”, he knows the final product market prices (logs price for heating, stakes, beam for house’s framework...) from which he retrieves every cost engaged for wood transformation to have an idea of the price he can sell wood to transformative actors such as sawmill owners. From that price, he retrieves his own costs engaged to cut the “Trees” and he obtains the price he gives to “Owners”. On Fig. 5, transformative actors are parts of the supply chain (in green) but we have not chosen to implement it in the model as agent because we want to focus on the beginning of the value chain where the difficulties are concentrated in Cévennes area. Indeed, from the discussions hold during the PARDI processes, stakeholders have insisted on the fact that they know how to transform and valorise the wood but the main problem is to extract the wood from the Cévennes forest.

The size of an Agent-Based Model depends on the implementation of the case study. However, it is possible to give an indication by summing the parameters of the model. Some of the parameters are geographically defined and thus depend on the size of the map. In the case study presented in this paper the map resolution is 56 pixels times 28 pixels = 1568 pixels. Therefore, as there is 15 parameters per pixel it makes 23 520 parameters. In addition, some other parameters are defined at the parcel scale (aggregation of pixels): there is 113 parcels and 8 parameters defined in parcels so 904 then 24 424 parameters. There is also 50 not geographically defined parameters so there is a total of 24 474 parameters in our implementation of the model.

In the next section, we will test our ABM on a theoretical case study, in order to understand better how it works and assessed its sensibility.

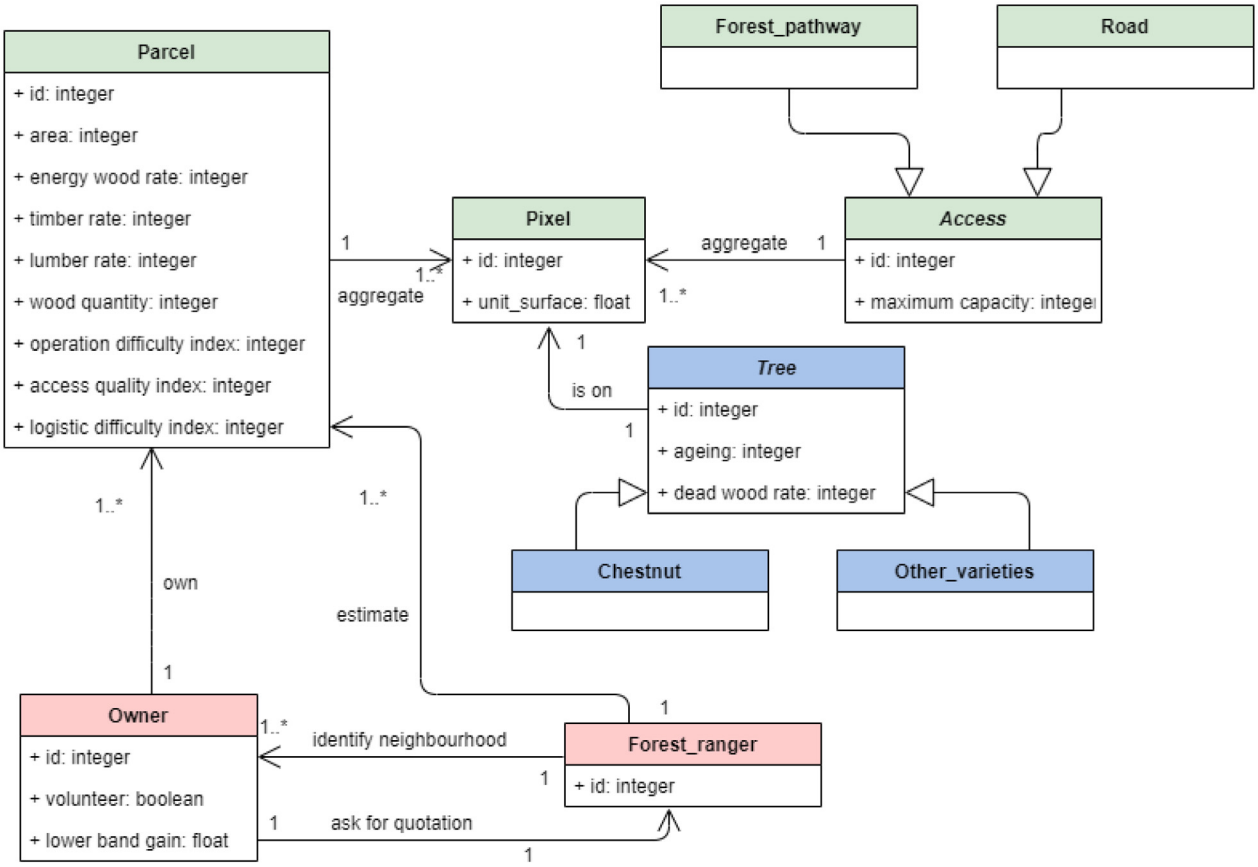

Fig. 7. ABM class diagram.

4.4. Step 4: scenario analyses

4.4.1. Preliminary results and sensitivity analyses

Before studying our case study, conditions of a successful negotiation between "Owners" and "Forest ranger" need to be assessed in order to determine parameters that influence the most the results. Indeed, as we are looking for the best action levers to unlock the resistance that forest plot owners have to remove declining wood from their land, we need to understand where actions are the most effective. Here, the main purpose of the sensitivity analyses is to reduce uncertainty on reality by going back and forth between the reality and the model before interpreting results of the scenario analyses. It differs with classical approaches where sensitivity analysis is presented after the results because our proposition is not classical.

There are mainly two kinds of parameters that influence the negotiation between "Owners" and "Forest ranger": the site size – that is to say the wood quantity to cut in cubic meters (m^3)-, and the difficulty indexes.

First on Fig. 8, the site size varies thanks to wood volume on site in m^3/ha (from 110 to 180 m^3/ha) and site area in ha (from 8 to 35 ha). The first values from 110 to 150 m^3/ha for a site area of 8 ha are not shown because the values are negative. Indeed, if the parcels have too poor conditions, forest plot owners need to pay forest ranger to clean the parcels, but the price calculation is lower than from the one we are focusing on in this study. Therefore, showing these negative values is not recommended. T1, T2, T3 denotes the three types of parcels we are studying:

- Parcels of type T1 have 100% of wood that can be valued as fuelwood,
- Parcels of type T2 have 85% of fuel wood, and 15% of wood that can be valued as service wood (poles, posts, wooden sticks and wooden stakes),
- Parcels of type T3 have 85% of fuel wood, and 15% of timber logs.

The red line represents the limit value of the gain that forest plot owners are ready to accept at the end of negotiations. If the bar graph is under the red lines, site conditions are not good enough and "Owners" would not accept the price given by "Forest ranger". Every numerical value has been chosen thanks to Cévennes area expert consulting.

Parcels of type T3 are profitable from 1360 m^3 of roundwood whereas parcels of type T1 and T2 are profitable from 1950 m^3. Indeed, final products derived from parcels T3 have higher value than the one of parcels T1 and T2. Therefore, gains at the beginning of the value chain are also more attractive. Under, 1950 m^3 parcels of type T2 are less profitable than T1 parcels. Yet, products derived from parcels T2 should be valued at higher price than T1 because products from T2 have higher added value than the one from T1. Nevertheless, the quantity of wood is not high enough to justify the cost engaged for operation and transport from the forest to the wood processing plant, thus it jeopardizes the economic profitability of parcels T2.

On Fig. 9, we fix the site size at 145 m^3/ha for 19 ha (2755 m^3) to make sure that every type of parcels are profitable. The difficulty indexes vary, respectively as follow: logistic difficulty takes the values[0; 2; 4], operation difficulty takes the values [0; 2; 4], access quality takes the values [0; 2.5; 5]. When one of the index varies the others takes their median value. Blue, orange and green bars represent the forest owner gain at the median value of difficulty indexes for, respectively parcels of type T1, T2 and T3. Er-

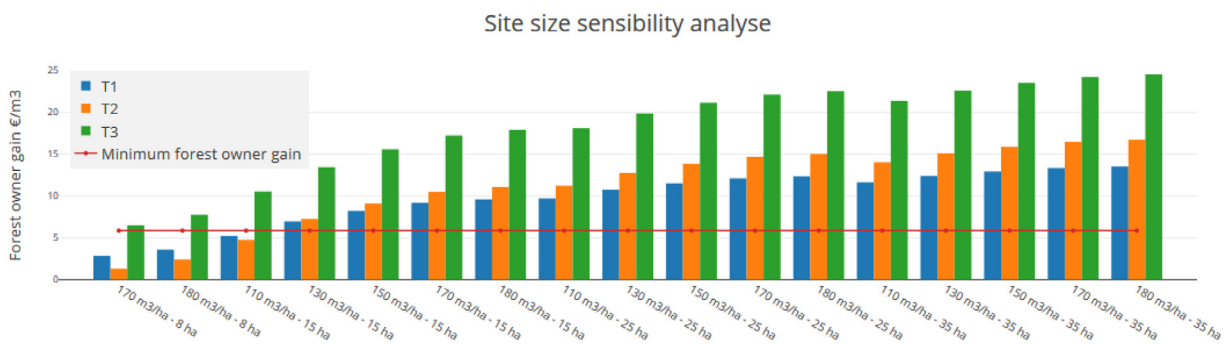

Fig. 8. Site size sensibility analyse – T1 parcels of type 1 100% fuelwood, T2 parcels of type 2 85% fuelwood and 15% wood service, T3 parcels of type 3 85% fuelwood and 15% timer logs.

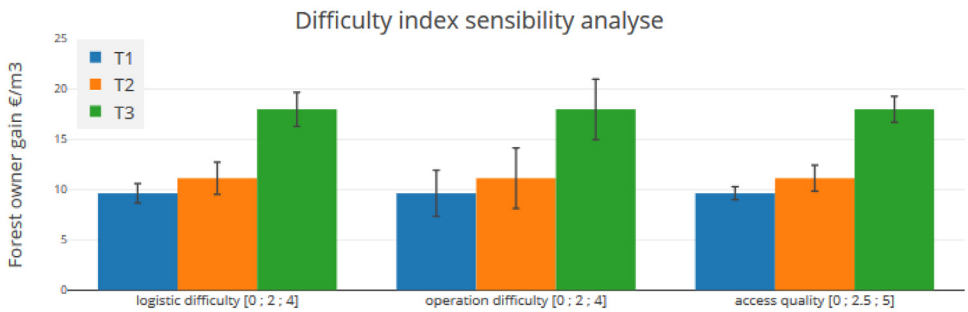

Fig. 9. Difficulty index sensibility analyse – T1 parcels of type 1 100% fuelwood, T2 parcels of type 2 85% fuelwood and 15% wood service, T3 parcels of type 3 85% fuelwood and 15% timer logs.

ror bars show the forest owner gain when difficulty indexes are at their minimum or their maximum values.

It appears that operation difficulty variation is the most sensitive parameter in our model (error bars for operation difficulty are bigger), followed by logistic difficulty and access quality. Therefore, at equal site size, operation difficulty is more likely to jeopardize economic profitability than other difficulty indexes.

To summarize, sites under 1360 m^3 for parcels of type T3 and 1950 m^3 for parcels of type T1 and T2 will not be harvested due to economic reasons. Nevertheless, the difficulty indexes can influence the site profitability from +/-3 €/m^3 to less than +/-1 €/m^3 and make sites profitable (if conditions are good) or not (if conditions are less favorable).

Now that we know the profitability limit according to the site size, it will be possible to understand why sites can be harvested or not when studying our case study in the next section. In addition, we also know that the model is more sensitive to operation difficulty index than to others so in the case study we will try to compensate exploitation cost with subsidies for instance.

4.4.2. Case study

Presentation. The case study is inspired by the Cévennes area. Fig. 10 shows the map of parcels and owners (small red and blue houses) as well as the forest view. On the map, accesses are in grey (light grey represents roads, dark grey represents forest pathways). Blue owners are volunteers as explained in Section 4.4 whereas red one are not. On the forest view, circles represent chestnut trees while triangles are other species (maritime pine for instance). Trees in green have less than 25% in volume of dead wood, light brown trees have more than 25% and less than 50% of dead wood, brown trees have dead wood rate between 50 and 75%, dark brown trees have more than 75% of dead wood.

On Fig. 10(a) we show the wood quantity of the volunteer owner and its direct neighborhood. The sum of wood quantities is equal 2150 m^3, which is above the two limits highlighted in the previous section. Therefore, the volunteer forest plot owner asks a forest ranger to make a quote. The latter proposes a price to the owner and its neighborhood in order to increase the profitability of the site. This price is such that it makes owners gain equal to 6.7 €/m^3 which is above the limit of 5.9 €/m^3, so site is accepted and the forest ranger cuts the trees (Fig. 11(a)). Then, trees grow again and after 1 year trees reach a size such that non-expert eyes cannot tell the difference.

This first simulation shows the importance of forest owner gathering in order to make site profitable. Indeed, if the volunteer owner had been alone the site would not have been harvested because of wood quantity lack. New trees are in green because they are not affected by wood degeneration yet. Therefore, the more there are forest logging the better will be the chestnut forest sanitary condition.

Thus, the main idea of the next section is to find solutions to increase the forest logging and as a result enhance the forest sanitary condition.

Results. In this section, we will put ourselves in a decision maker's shoes, who has some money to invest in actions to improve the chestnut forest sanitary condition. As sites are on forest owner initiative, the policy makers will first invest on a campaign to raise forest owner awareness on the necessity to maintain their forest: the strongest argument can be the fire risk as population fear it. The consequences on our model is the increase in volunteer forest owners (Fig. 12) which is positive as more sites will be proposed to harvester. Thus, the probability of accepted sites will increase, therefore the exploited forest area will increase too. We identify forest owners thanks to their ID.

Thanks to the awareness of forest owners 1, 2 and 4 the forest logging increases from 17 ha (in the simulation of the previous section) to 75 ha, which allows the wood extraction of 10 210 m^3 (against 2150 m^3 in the simulation of previous section). Nevertheless, the parcels from forest owner 3 and 5 are not harvest because

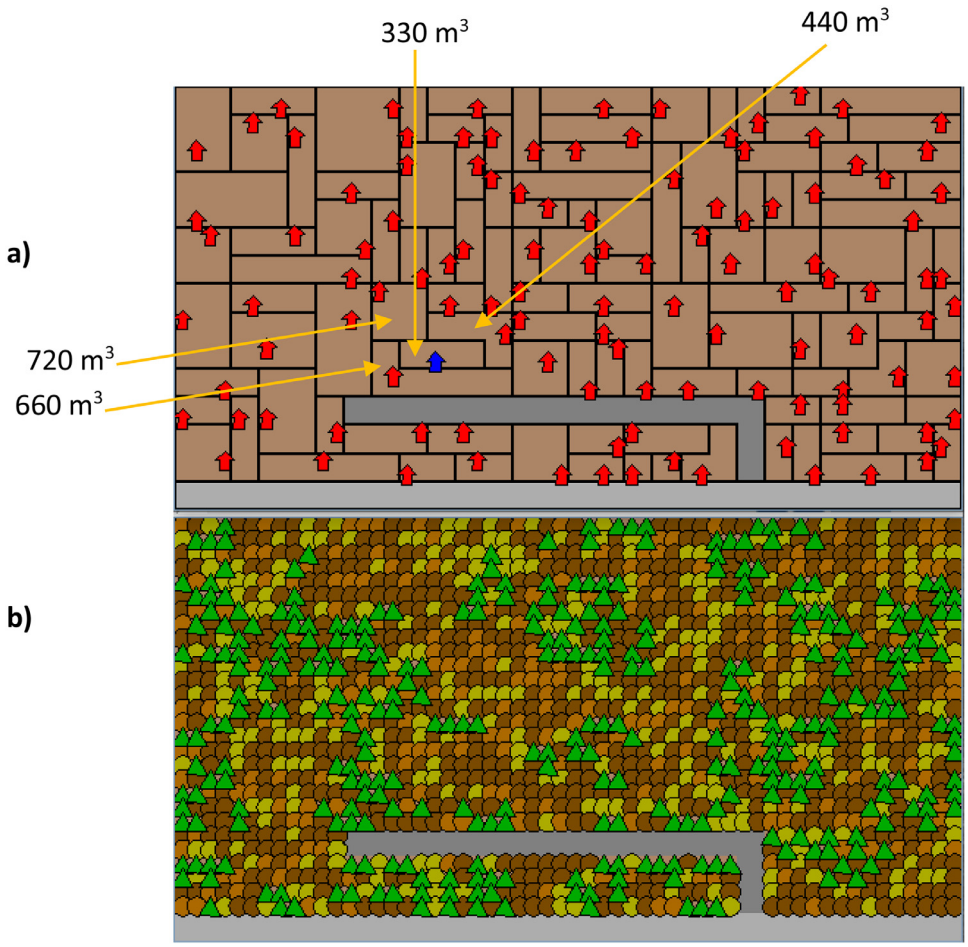

Fig. 10. Case study's map - (a) parcels and owners map (blue house volunteer forest plots owner, red house not volunteer forest plot owner), (b) representation of the forest landscape (green = no deadwood, light brown between 25 and 50% of deadwood in volume, brown between 50 and 75% of deadwood, dark brown more than 75% of deadwood) (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

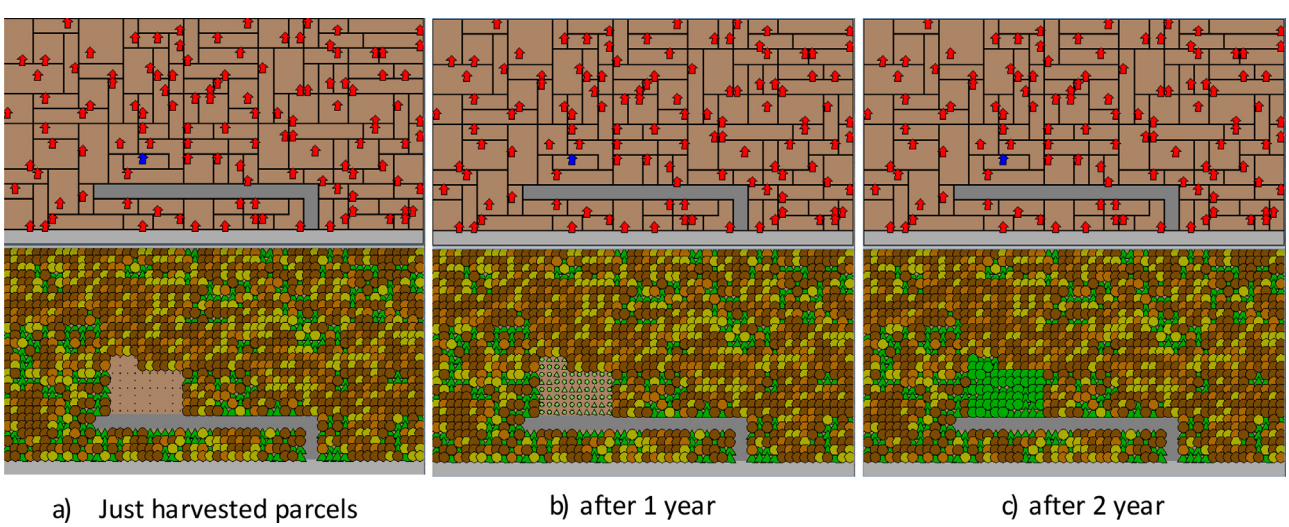

Fig. 11. Forest operation on sites (sites = group of neighbors parcels).

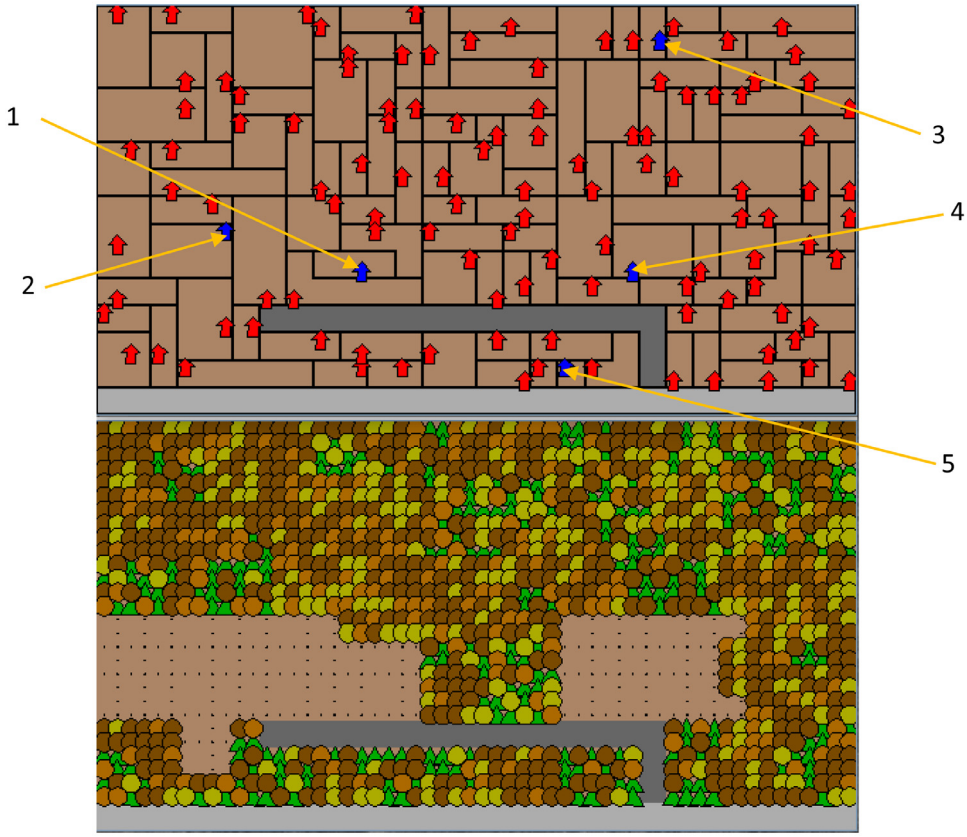

Fig. 12. New owners denoted by their ID (blue house volunteer forest plots owner, red house not volunteer forest plot owner) and forest harvesting results (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

Table 1
Forest owner subsidies influence.

Forest owner subsidy		0 €/m³	1 €/m³	2 €/m³	3 €/m³
Forest owner gain	*Site 1*	4.9 €/m³	5.9 €/m³	6.9 €/m³	7.9 €/m³
	Site 2	3.9 €/m³	4.9 €/m³	5.9 €/m³	6.9 €/m³
	Site 3	2.9 €/m³	3.9 €/m³	4.9 €/m³	5.9 €/m³
Logging area		0 ha	11 ha	23 ha	33 ha
Wood quantity		0 m³	2 240 m³	4 512 m³	7 802 m³
Budget allowance		0 €	2 240 €	9 024 €	23 406 €

they do not fulfill the two main parameters previously identified (i.e. site size and difficulty indexes). In the case of forest owner 3, the parcels are too far from accesses (high difficulty indexes) so even if he is volunteer the site cannot be harvested. Regarding forest owner 5, his parcel and the ones of its neighborhood are small (small site size), therefore, the wood quantity is not sufficient to be profitable. A strategy could be to ask to a wider neighborhood in order to increase the profitability.

Another strategy would be that the decision maker subsidizes the forest owner or forest ranger in order to improve the economy of forest logging. Nevertheless, in addition to the wood price, the forest owner charge 10% of the transaction for the forest management service (meaning maintenance of the forest that leads to the wood quality at the time of the transaction). Therefore, we have:

$$owner_{gain} = \frac{Transaction}{1 + 10\%}$$

If the decision maker decides to subsidize the forest ranger, this comes down to finance the forest management service. For instance, let's assume the decision maker wants to increase owner gain by 1 €/m³. When subsidize the forest ranger he needs to pay:

$$owner_{gain} = \frac{Transaction + SUBSIDIES}{1 + 10\%} = \frac{Transaction + 1\ €/m^3.(1 + 10\%)}{1 + 10\%}$$

So the necessary subsidies will be equal to 1.1 €/m³ instead of 1 €/m³ by subsidizing directly the forest owner instead. Therefore, the decision maker should rather subsidize the forest owner instead of the forest ranger in order to reduce the subsidy budget.

Such subsidies are relevant for small sites close to the profitability limit (forest plot owner gain of 5.9 €/m³). Let us consider such conditions for the three sites proposed on Fig. 13(a).

We consider four cases: no subsidy, subsidy of 1, 2 or 3 €/m³, and we compare how much area is unlocked thanks to these subsidies. Table 1 gathers the numerical results.

Obviously, the higher the subsidy is the more it unlocks area and wood quantity. Nevertheless, the budget allowance grows faster than unlocked resources. The decision maker has to find compromise between the latter and the necessary amount of budget allowance.

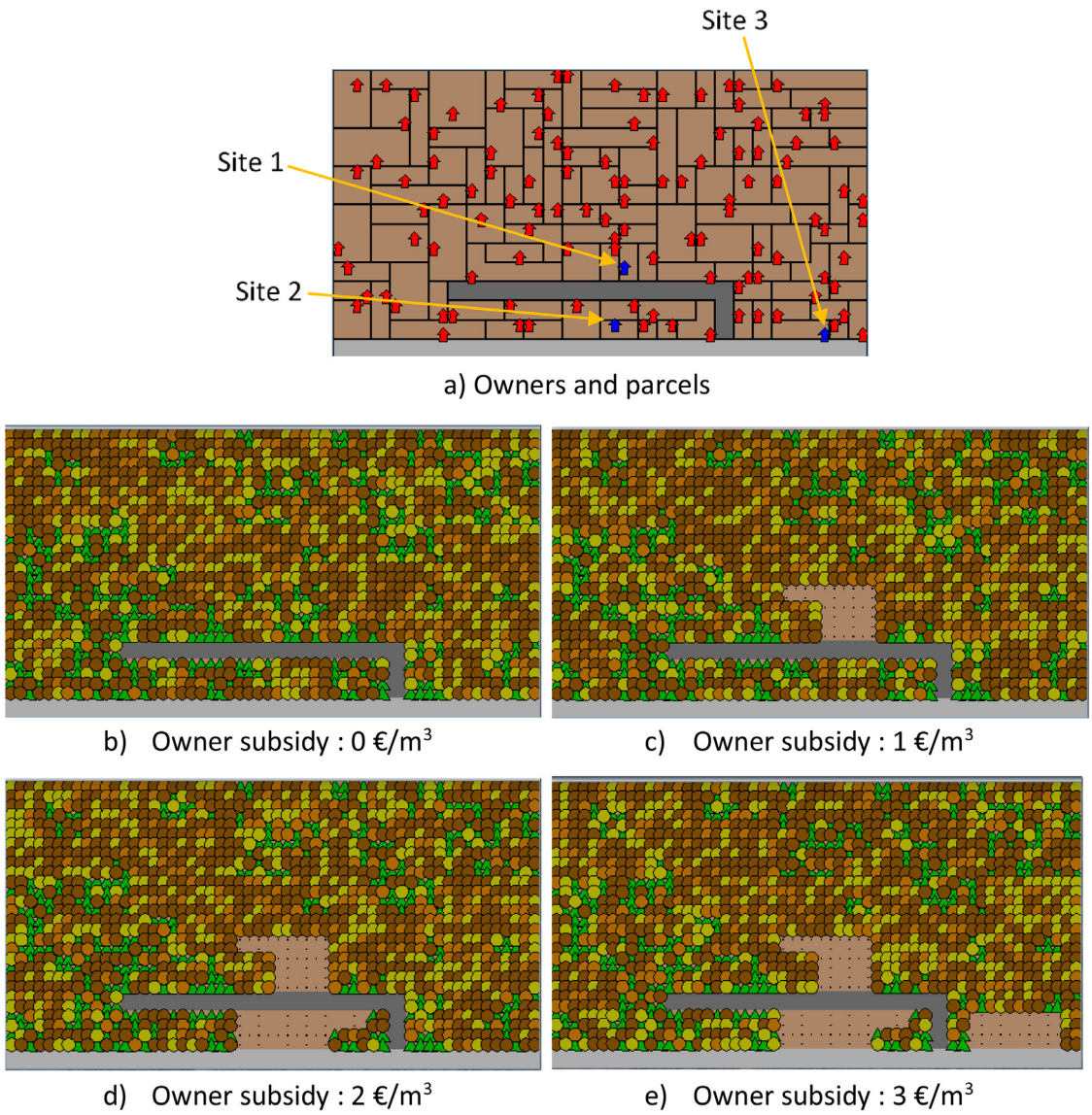

Fig. 13. Influence of subsidies on sites close to the profitability limit.

5. Conclusion and perspectives

This paper presents a new multi-agent based approach integrating all stakeholders requirements in the co-construction of a simulation model and in the development of management scenarios. The four-step methodology proposes a shift from a modeling based on a centered or rationalist approach towards a collaborative approach (decentralized) which needs the emergence of new tools that focus on co-construction of models. The goals, boundaries, context and hypotheses are first specified. In participative modeling, mapping stakeholders is a crucial step. The expectations of the actors are different according to their positions with respect to the system, therefore the mapping is organized according to the different levels of decision making. Then the superstructure definition is established with the PARDI (Problem, Actors, Resources, Dynamics, and Interactions) method. These five subsets allow the progressive emergence of a shared representation of the components and dynamics of the system. Thanks to the PARDI method, the co-creation of the multi agent based model is straightforward as agents, objects and concepts that need to be implemented into ABM are clearly described. The main advantage of participatory modeling is that it imposes a multi stakeholders vision of the problem and therefore the search for a modeling consensus. Moreover, with this approach, the scope is broader allowing for direct inclusion into the model of the social, economic, environmental and political dimension (not necessarily in the form of objectives as traditional PSE approaches).

The proposed methodology was applied to a case study related to the Cévennes area chestnut degeneration and its consequences. The "P" of the PARDI method raise the following question:

> *"How to federate Cévennes' actors to set up action in order to remove declining chestnut and prepare tomorrow forest?"*

We have developed an Agent-Based Model to answer that question by focusing on political strategies that can be employed to activate levers for action. In the case study, we have shown how decision makers can use our model to test these strategies. Especially, we have shown that cooperation between forest owners is mandatory. Indeed, as Cévennes area's parcels are numerous but small, it is necessary to gather parcels to make bigger sites and thus increase the economic profitability. The cooperation with the neighbors could lower valorisation of high value wood due to other less qualitative parcels agglomeration. However, such cooperation is necessary to unlock the wood extraction from poor parcels, and

thus make the forest regenerate everywhere. One way to encourage the cooperation can be to subsidize forest owners that gather themselves but whose cooperation is not sufficient to reach the profitability limit as shown in results section.

The next steps is to test our Agent-Based Model on real case studies, which implies considering the use of Geographic Information System (GIS) data to build the forest and parcels maps. The main idea is to produce relevant results for the local stakeholders and trigger transformative decision for the Cévennes area. In addition, technology transfer to the local stakeholders is important in order to empower them with our research outcomes. Therefore, the packaging of our model, including its GIS components, in a complete user-friendly software will be achieve in the near future.

Authors want to raise attention on three critical issues to enhance stakeholders' participation in further work. First, process system engineering skills are required to identify and model the peculiarity of the process, all types of legitimate knowledge, and to be sensitive to the power relationships among the people involved in the collaborative workshops to avoid modeling them. Second, special attention has to be paid to the representativeness of the actors involved. Thus, the method should be adapted to a particular decision making context, and should take into account consideration of the objectives, and status of participants and their level of engagement. Third, the objectives of the collaborative process must be clearly defined and agreed upon at the beginning of the process, and regularly revisited while proceeding. Indeed objectives are likely to be frequently challenged due to the complexity and uncertainty of the context but also due a better understanding of the studied system during progress in the methodology steps (thanks to the collaborative exchange). Moreover, the application of the PARDI method has demonstrated strengths in understanding stakeholders' perspectives and constraints, and providing an effective way to get to a shared model of a complex system. It allows an integration of social, environmental, politics, technical, and scientific knowledge in order to be focused on the principal characteristics of the system, and providing access to different approaches to model a situation. In addition, the methodology is transdisciplinary by nature therefore research gathering political science, economy, game theory and participatory research should be very interesting in order to better integrate democracy in public policy.

The contribution of our new participative approach for PSE community should be investigated in future research. First, it could be possible to structure a bi-level decision tool with the developed ABM at the hear of a mathematical optimization model meant to optimize some overall objective rather than the objectives that the stakeholders selected. It could show stakeholders what is possible if they are open to compromise or tweak their priorities/objectives. Another opportunity might be to apply the PARDI method to develop an ABM while simultaneously developing a "classical" PSE optimization model of the same system (e.g. multi-objective MINLP, multi-level, game-theoretic, etc.) seems to be mandatory. The aim would be to see how different the results are and how each stakeholders' objectives are satisfied (or not satisfied) in either approach. However, it implies new questions: Should the study be made by the same person? If yes, how the results of one approach would influenced the other one? What are the bias? In the case that two persons conduct parallel studies, how to take into account the influence of the two persons? Such study must include cognitive/social approach in addition to PARDI and classical PSE approaches.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

CRediT authorship contribution statement

Anastasia Roth: Conceptualization, Methodology, Writing – original draft. **François Pinta:** Conceptualization, Methodology, Writing – review & editing, Supervision. **Stéphane Negny:** Conceptualization, Methodology, Writing – review & editing, Supervision. **Ludovic Montastruc:** Conceptualization, Methodology, Writing – review & editing, Supervision.

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