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Multi-Agents Generating Alternative Plans in Local Land-Use Planning

Specifying their reasoning and interaction

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Abstract: This paper addresses the MASQUE multi-agent framework for generating alternative plans in local land-use planning, In this framework agents represent land-use experts and initiate the development of plan proposals and request each other to express their claims in order to incrementally draw up these proposals. Presented is a probabilistic approach to the implementation of those agents to enable them to make decisions under uncertainty. It is described what personal and collective beliefs they construct and use in order to strategically choose their actions. Negotiation takes place between the initiating agent and the others in order to reach agreement on the incorporation of the claims. The negotiation is organized as an iterative process in which both parties consider conciliatory adjustments of their strategies, and thus their decisions, in order to try to find mutually accepted solutions.

1. INTRODUCTION

Multi-agent technology "gives rise to a new generation of application structures, with a high degree of anthropomorphy and, hence, understandability by the users" (Cuena & Ossowski, 1999). Also in the academic field of urban planning this potential has been recognized, as can be seen from the increasing number of agent-based simulation tools being developed (see e.g. Parker et al., 2003 for an extensive review). The vast majority of these tools simulate the developments in an area by modelling the individual behaviour of future users, for instance households. An agent then represents such a user and is situated *inside* the environment. This approach has proved to result in promising tools for evaluating the effects of different policy scenarios. Only rarely (Ferrand, 1996; Ligtenberg et al. 2001) attempts are made to situate agents *outside* the environment, having them represent the various decision-makers involved in the practice of urban plan development. This approach, however, offers complementary opportunities to improve the quality of decision-making in shaping the urban environment by means of multi-agent technology, as it will bring us tools to generate alternative plans computationally, while offering insight in the effects of decision-makers' trade-offs during the group decision-making process. In order to explore and demonstrate how the knowledge of multiple disciplines can be incorporated and synergistically utilized in a Planning Support System (PSS), a multi-agent framework referred to as MASQUE is being developed for generating alternative plans. The focus of this framework is on local land-use plans in which, according to Dutch practice, legally-binding regulations for permissible land-use(s) in designated zones are laid down, either generally or more detailed. MASQUE suggests a probabilistic approach to the agent specification and implementation in order to let the agents make decisions under uncertainty, a phenomena abundantly present in the urban plan development process. The key components are concepts of beliefs and strategic actions.

This paper elaborates on earlier work (Saarloos et al. 2003), in which the organizational characteristics of the framework were described. Section 2 will briefly recall these characteristics in order to define the context of the current paper. Then, we will focus on the different elements of reasoning and action that are used by the agents in section 3. This is followed by a description of the protocols that have been defined for the interaction between the agents in section 4. Finally, conclusions will be drawn and the presented model will be discussed to identify issues for future work.

2. A MULTI-AGENT FRAMEWORK FOR ALTERNATIVE PLAN GENERATION

2.1 Organization

As mentioned above, the MASQUE framework serves for generating alternative plans in local land-use planning. It fully exploits the anthropomorphic nature of the multi-agent technology by introducing a group of so-called "Domain Agents" (further addressed to as "agents") that represent the various disciplinary experts involved in the plan development process, like a housing expert, a transportation expert, a services expert, and a greenspace expert, based on a classification adopted from the Dutch IMRO data model (Ravi, 2000). These agents form a *team* that is at the disposal of the system user, i.e. urban planner. As such, the user can commission the agents to cooperatively generate a set of alternative plans based on the situation and preconditions given. Agents will first generate *plan proposals* and then evaluate these proposals. Plan proposals that successfully pass the evaluation phase will be given the status of *alternative plans*.

The objective of our concept is to have a comprehensive process that results in a compact but distinctive set of alternative plans. This is established by means of a "viewpoint approach" in which every agent autonomously and pro-actively initiates the development of plan proposals and requests others to make contributions. This implies that an agent can take on two *roles* during the development of a plan proposal: it can be either the "Initiator", who decides upon how to integrate the contributions into a proposal, or a "Participant", who contributes to a proposal that is initiated by another agent.

2.2 Assumptions

Two sources with information about the study area are assumed to be available before the alternative plan generation process starts. First, there is an *Inventory* database that contains information about the environment, i.e. attribute data concerning the study area and its surroundings. Second, there is a *Plan Program* that, for every land-use, lists the task size (i.e. the area to be claimed) and possible preconditions (e.g. regarding clustering, adjacency, and accessibility)[1].

In the remainder of this paper, we assume a discretization of the environment in space, which results in a raster representation of the study area and its surroundings. Consequently, the pieces of land are equally sized square cells. This implies for instance that a task size can be expressed as the number of cells to be claimed for each land-use.

3. ELEMENTS OF REASONING AND ACTION

In general, an agent's task is to claim cells in the study area for its land-use according to the task size and preconditions formulated in the Plan Program (see section 2.2). Decisions are made based on applying personal

[1] Clustering, adjacency and accessibility are here considered as measures that can be expressed in both positive and negative values. So, when they are mentioned it includes respectively non-clustering (i.e. spreading), non-adjacency and non-accessibility.

knowledge to the information that is extracted from the environment and/or received from other agents. In the role of Initiator, an agent has the additional task to assign cells to the different agents (i.e. land-uses), which requires the capability to resolve possible conflicts of interests between the different parties. This section will describe the various elements that agents use as either Initiator or Participant in order to reason and act.

3.1 Personal knowledge bases

An agent decides whether or not to claim cells for its land-use based on the expected utility of those cells, an index that the agent determines from applying a decision model.[2] This model consists of a set of rules to judge the suitability of each cell based on both its physical and spatial attributes. Every rule addresses a specified attribute, represented in terms of an exhaustive set of mutually exclusive states, and determines the utility value based on the observed state of that attribute. For instance, a housing agent could apply a rule for the slope of cells, setting the conditional utilities to ‘flat’ = 100, ‘minor’ = 50, and ‘major’ = 0.

3.2 Beliefs

The more land-uses have to be allocated in the study area, the more likely conflicting claims will occur. To an agent it is unknown (or unsure) what requirements and/or preferences other agents will try to meet, how persistent they will do so, and what trade-offs they will make when joint solutions have to be found. Consequently, an agent is faced with uncertainty in its decision-making and limited to developing beliefs about what would be most attractive to its land-use and about what would be most probable considering all interests together.

3.2.1 Believed goal states

The belief an agent constructs about what allocation would be most attractive to its land-use is referred to as that agent’s **believed goal state**. This *personal* belief addresses all cells in the study area, consisting of I rows and J columns of cells, and indicates for every cell the probability that an agent x will claim it, as believed by that agent at time t:

[2] See Ma et al. (2004) for more details.

$$Bel\{GS\}_x^t = \begin{bmatrix} P\left(C_{11,x}^{g,t}=1\right) & \dots & P\left(C_{1J,x}^{g,t}=1\right) \\ \vdots & \ddots & \vdots \\ P\left(C_{I1,x}^{g,t}=1\right) & \dots & P\left(C_{IJ,x}^{g,t}=1\right) \end{bmatrix} \tag{1}$$

where $P\left(C_{ij,x}^{g,t}=1\right)$ is the probability of cell *(i,j)* being claimed by agent *x* at time *t* and stored in that agent's goal state *g*, with *i = 1..I* and *j = 1..J,* and $C_{ij,x}^{g,t}$ expresses whether agent *x* claims (1) the cell or not (0). A believed goal state is constructed in three consecutive steps. First, the agent applies a decision model in order to determine the **expected utility** *U* of each cell based on the information available. At the start of the process this information is limited to the attribute data found in the Inventory database and the Plan Program (see section 2.2). During the process more accurate information becomes available when decisions are being made. The decision model computes:

$$U_{ij,x}^t = f\left(Z, L^c, P\left(L^f\right)\right) \tag{2}$$

where U_{ij}^t is the expected utility, a value within the range of [0,100], of cell *(i,j)* as believed by agent *x* at time *t*. Z , L^c and L^f are vectors of relevant attribute values of cell (*i,j*) regarding respectively:

- The physical characteristics of the cell (e.g. soil conditions).
- The location of the cell relative to *current* land-uses, i.e. to cells in the surroundings of the study area for which land-uses are considered given.
- The location of the cell relative to *future* land-uses, i.e. to other cells in the study area for which land-uses are *uncertain*.

It should be noted that the last category concerns probabilistic data that is given by the believed study area future, *Bel{SAF}* (see 3.2.2). During the process, however, more and more decisions will be made and the uncertainty (or entropy) of this data will gradually be reduced. Thus, the probabilities will gradually converge towards facts.

Second, the agent converts the expected utility *U* of each cell into a **preliminary probability** P^* that expresses the basic chance that the agent claims the cell. This $U \rightarrow P^*$ conversion is assumed to be represented by an s-shaped curve, which means that the increase in the probability of claiming a cell will gradually increase with an increasing utility to a certain inflection point beyond which the increase will gradually decrease. The following equation is proposed:

$$P^{*}\left(C_{ij,x}^{g,t^{*}}=1\right)=\frac{1}{1+e^{\beta(\alpha-U_{ij,x}^{t})}} \tag{3}$$

where α is a parameter that is proportional to the average utility $\overline{U}^{t}$ of all cells in the study area at time *t*. It is for cells with a value around this average that the agent wants to differentiate the probability most. A higher average leads to a higher α and will result in a horizontal right shift of the s-curve. Parameter β is inversely proportional to the standard deviation σ^{t} of the whole set of cells in the study area at time *t*. It sets the width of the area within which the agent will differentiate most. A lower standard deviation results in a higher β and will make the slope of the curve steeper. We assume the following default parameter settings:

$$\alpha=\overline{U}^{t} \text{ and } \beta=\frac{3}{\sigma^{t}} \tag{4}$$

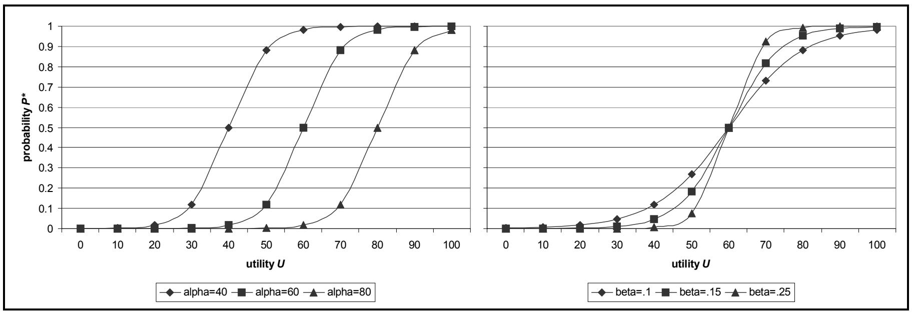

Figure 1. Illustration of alpha sensitivity (beta=.2) and beta sensitivity (alpha=60)

Figure 1 show the sensitivity of the method to different values of the parameters α and β. When the conversion is completed, the preliminary probabilities for the whole study area are normalized so that their sum equals the agent's task size.

Third and last, the agent takes into account the desired level of clustering for its land-use and identifies those pieces of land that together form the best allocation. For this, the agent converts the preliminary probability P^{*} for each cell into a **final probability** P, by making the latter conditional on the probabilities of claiming the adjacent cells in its neighbourhood H_{ij} that consists of four "edge neighbours" and four "corner neighbours" (see Figure 2). For an agent *x* the $P^{*} \rightarrow P$ conversion is implemented as:

$$P\left(C_{ij,x}^{g,t}=1 \middle| C_{ij,x}^{g,t*}=c_{ij}, C_{H_{ij,e},x}^{g,t*}=c_{H_{ij,e}}, C_{H_{ij,c},x}^{g,t*}=c_{H_{ij,c}}\right)$$
$$=(1-\varphi)C_{ij,x}^{g,t*}+\varphi\left(\gamma\overline{C_{H_{ij,e},x}^{g,t*}}+(1-\gamma)\overline{C_{H_{ij,c},x}^{g,t*}}\right) \quad (5)$$
$$\forall\, c_{ij}\in\{0,1\}, c_{H_{ij,e}}\in\{0,1\}, c_{H_{ij,c}}\in\{0,1\}$$

where φ is a parameter [0,1] indicating the desired level of clustering of agent *x*, and γ a parameter [0,1] setting the relative value that this agent *x* gives to the average preliminary probability of the "edge neighbours" $H_{ij,e}$ as compared to the value given to the average preliminary probability of the "corner neighbours" $H_{ij,c}$.

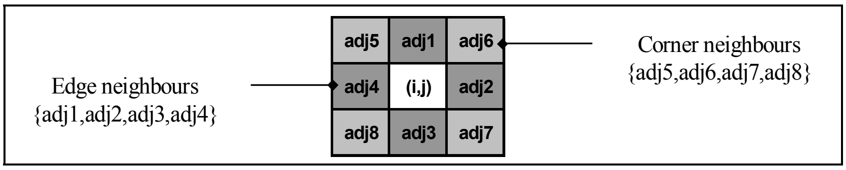

Figure 2. Cell *(i,j)* and its neighbourhood H_{ij}

Table 1 shows an example of how conditional probability tables (CPTs) are used as the format to document the proposed method for taking into account clustering.

Table 1. Example of a CPT for taking into account clustering for a cell *(i,j)* , φ = .8, γ = .75

$C_{ij,x}^{g,t*}$	$C_{H_{ij,e},x}^{g,t*}$ *of edge neighbours*				$C_{H_{ij,c},x}^{g,t*}$ *of corner neighbours*				$P\left(C_{ij,x}^{g,t}=1\right)$
	adj1	*adj2*	*adj3*	*adj4*	*adj5*	*adj6*	*adj7*	*adj8*	
1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	0	.95
1	1	1	1	1	1	1	0	1	.95
1	1	1	1	1	1	1	0	0	.90
…	…	…	…	…	…	…	…	…	…
0	0	0	0	0	0	0	1	1	.10
0	0	0	0	0	0	0	1	0	.05
0	0	0	0	0	0	0	0	1	.05
0	0	0	0	0	0	0	0	0	0

The CPT shows how the final probability *P* of an agent *x* claiming a cell *(i,j)* (see most right column) is conditional on the set of claims C_x^* this agent makes for that cell and its eight neighbours (see other columns). Every row in the table is called a "state" and can be read as an "if-then" rule. When applying the CPT, the actual inputs – the preliminary probabilities P^* of the cell and its eight neighbours – are used and multiplication takes place. The example assumes a .8 desired level of clustering (φ) and a .75 versus .25 value judgement of respectively edge (γ) and corner neighbours ($1-\gamma$).

The resulting values *P* are once more normalized in order to make their sum for the whole study area equal to the task size. All the (normalized final) probabilities together finally make up the agent's believed goal state, *Bel{GS}* (see equation 1). This belief is either passed directly to the Initiator for initializing the believed study area future (see section 3.2.2), or privately used by the agent itself for strategically deciding which claims to express (see section 3.3.1) or evaluating suggested assignments (see section 3.3.3).

3.2.2 Beliefs about the future state of the study area

The belief an agent has about the most probable future state of the study area is referred to as the **believed study area future**. This belief is assumed to be a *collective* belief, which implies that all agents share it. The belief gives an overview of the prevailing expectations regarding the study area's future state, and hence is kept up-to-date during the development of a plan proposal. Updating this belief is made the responsibility of the Initiator due to the fact that this agent manages the process of integrating the different contributions. Participants cannot update this belief; the Initiator simply informs them. The collective belief addresses all cells in a study area, consisting of *I* rows and *J* columns of cells, and gives for every cell the probability distribution across the candidate land-uses as believed by Initiator *y* at time *t*:

$$Bel\{SAF\}_y^t = \begin{bmatrix} P\left(L_{11}^t\right) & \cdots & P\left(L_{1J}^t\right) \\ \vdots & \ddots & \vdots \\ P\left(L_{I1}^t\right) & \cdots & P\left(L_{IJ}^t\right) \end{bmatrix} \tag{6}$$

where $P\left(L_{ij}^t\right)$ is the probability distribution for cell *(i,j)* across a set *L* of *n* candidate land-uses as believed by Initiator *y* at time *t*:

$$P\left(L_{ij}^t\right) = \left\{P\left(A_{ij,1}^t = 1\right), P\left(A_{ij,2}^t = 1\right), \ldots, P\left(A_{ij,n}^t = 1\right)\right\} \tag{7}$$

where $P\left(A_{ij,x}^t = 1\right)$ is the probability of cell *(i,j)* being assigned to land-use *x* (by Initiator *y*). For initialization (*t = 0*) of *Bel{SAF}* the Initiator uses the task sizes as stated in the Plan Program (see 2.2) to set a basic probability distribution across land-uses for every cell in the study area. During the plan generation process (*t > 0*), Initiator *y* performs belief updates by applying a real-time defined function f_y, that expresses the belief to be conditional on the set of all received claims *C*, including its own (see 3.3.1):

$$Bel\{SAF\}_y^t = f\left(C_1^s, C_2^s \ldots, C_n^s\right)_y^t \quad \text{for } t > 0 \tag{8}$$

where C_x^s are the claims received from agent *x*, with index *s* indicating that it concerns *strategic* claims (see section 3.3.1). In order to perform a belief update the Initiator needs to balance the different inputs or interests against one another. Based on its personal requirements and/or preferences for adjacency and accessibility to other land-uses, and general requirements to ensure that common interests are taken into account, the Initiator defines the *importance* of each input, i.e. each Participant's claims. The belief update takes place per cell and is implemented as a logit model:

$$P\left(A_{ij,x}^t = 1 \middle| S_G\right) = \frac{e^{V_{ij,x}^t}}{\sum_{n \in G} e^{V_{ij,n}^t}} \tag{9}$$

where S_G is a vector consisting of G claims, and $V_{ij,x}^t$ is the input for land-use *x* at time *t* as weighted by Initiator *y*:

$$V_{ij,x}^t = w_{y,x} C_{ij,x}^{s,t} \quad \forall C_{ij,x}^{s,t} \in \{0,1\} \tag{10}$$

where $w_{y,x}$ reflects the importance that Initiator *y* gives to the input regarding land-use *x*, ranging from "no importance" (w = 0) to "high importance" (w=5).

Table 2. Example of a CPT for updating *Bel{SAF}* for a cell *(i,j)* at time *t*

$w_{1,1} = 5$	$w_{1,2} = 3$	$W_{1,3} = 1$	$Bel\{SAF\}_y$		
C_1^s	C_2^s	C_3^s	$P_y(A_1=1)$	$P_y(A_2=1)$	$P_y(A_3=1)$
1	1	1	0.867	0.117	0.016
1	1	0	0.876	0.118	0.006
1	0	1	0.976	0.007	0.018
1	0	0	0.987	0.007	0.007
0	1	1	0.042	0.844	0.114
0	1	0	0.045	0.909	0.045
0	0	1	0.212	0.212	0.576
0	0	0	0.333	0.333	0.333

Table 2 shows an example of the logit model in the format of a CPT for belief updating: an agent 1, being the Initiator, considers a set of three inputs $\{C_1, C_2, C_3\}$ and processes these by means of a personally defined weight set $\{w_{1,1}, w_{1,2}, w_{1,3}\}$.

3.3 Strategic actions

As mentioned, the general task of an agent is to express its **claims** when, as a Participant, being requested to do so by the Initiator of the plan proposal under development. As Initiator, an agent's task is to process all claims, including its own, and to express the resulting **assignments** towards Participants. The latter then have to **evaluate** these assignments to decide whether or not to agree. All these tasks require an agent to decide how to act based on the prevailing beliefs, implying that strategies are needed for how to combine these beliefs. Hence, execution of these tasks can be referred to as *strategic actions*.

3.3.1 Claims

When an agent, in the role of Participant, is requested to express its claims, it means that the agent is asked to indicate, for each cell, whether or not it wants to claim that cell. Hence, the claims for a study area, consisting of *I* rows and *J* columns of cells, as decided and expressed by agent *x* at time *t* are:

$$Claims_x^t = \begin{bmatrix} P\left(C_{11,x}^{s,t}=1\right) & \cdots & P\left(C_{1J,x}^{s,t}=1\right) \\ \vdots & \ddots & \vdots \\ P\left(C_{I1,x}^{s,t}=1\right) & \cdots & P\left(C_{IJ,x}^{s,t}=1\right) \end{bmatrix} \tag{11}$$

where $P\left(C_{ij,x}^{s,t}=1\right)$ is the *strategic* claim C^s of agent *x* for cell *(i,j)*, as expressed by that agent at time *t*. The agent's strategy relates to his decision about how to combine its personal believed goal state, *Bel{GS}* ("what is most attractive"), with the currently believed study area future, *Bel{SAF}* ("what is most probable") that was included in the Initiator's request. A Participant makes this decision in two steps. First, the agent updates its *Bel{GS}* by means of its decision model (see section 3.2.1) and based on the up-to-date probabilistic information that can be found in the received *Bel{SAF}*. Second, the agent decides how to combine the two beliefs. Obviously, the *Claims* can be simply based on only one of the beliefs, resulting in either a most opportunistic or a most democratic strategy. As opposed to such a *pure* strategy the agent can choose for a *mixed* strategy, taking into account both beliefs. Provisionally, this strategic decision of combining beliefs in order to define *Claims* is implemented as a weighted summation per cell:

$$P\left(C_{ij,x}^{s,t}=1 \middle| C_{ij,x}^{g,t}=c, A_{ij,x}^{t}=a\right)=\theta\, C_{ij,x}^{g,t}+\left(1-\theta\right) A_{ij,x}^{t} \qquad \forall\, c\in\left\{0,1\right\}, a\in\left\{0,1\right\} \tag{12}$$

where θ is a parameter [0,1] indicating the extent to which agent *x* pursues what is most attractive, $C_{ij,x}^{g,t}$ as found in its own *Bel{GS}*, against what is most probable, $A_{ij,x}^{t}$ as indicated by Initiator *y* in *Bel{SAF}*.

A similar continuation is proposed here as for constructing believed goal states (see section 3.2.1). The resulting claims are referred to as **preliminary claims** and normalized for the whole study area in order to make the sum of all claims – which are actually probabilities – equal to the task size. A consecutive step is used to take into account the desire for clustering and converts the preliminary claims into **final claims** that are normalized as well. All the (normalized final) claims together form the *Claims* that are communicated back to the Initiator.

3.3.2 Assignments

The Initiator processes *Claims* into *Assignments*, which means that this agent determines for each cell the probabilities for the different land-uses to be assigned to that cell. Hence, the *Assignments* for a study area, consisting of *I* rows and *J* columns of cells, as decided and expressed by Initiator *y* at time *t* are:

$$Assignments_{y}^{t}=\begin{bmatrix} P\left(L_{11}^{t}\right) & \cdots & P\left(L_{1J}^{t}\right) \\ \vdots & \ddots & \vdots \\ P\left(L_{I1}^{t}\right) & \cdots & P\left(L_{IJ}^{t}\right) \end{bmatrix} \tag{13}$$

where $P\left(L_{ij}^{t}\right)$ is the probability distribution as expressed by Initiator *y* at time *t* for cell *(i,j)* across a set *L* of *n* candidate land-uses (cf. equation 7). The construction of *Assignments* is implemented as a belief update, applying the logit model as depicted by equations 9 and 10. The Initiator takes a strategic decision concerning the weight set he applies for the model. When the *Claims* of one or more Participants are still missing – a situation that will occur during a sequential procedure (see section 4.2) – the Initiator will use believed goal states as input to the model instead.[3]

The resulting *Assignments*, $P\left(L_{ij}^{t}\right)$, are normalized in order to make, for each land-use, the sum of the probabilities of all cells in the study area equal to the task size for that land-use. These normalized *Assignments* are suggested to the Participants.

3.3.3 Evaluation of assignments

Having expressed *Claims* to the Initiator, a Participant will in return receive the *Assignments* suggested by the Initiator. It is now up to the Participant to compare the *Claims* made ("what was asked for") and the *Assignments* proposed ("what is offered in return") in order to judge whether or not the *Assignments* are acceptable. This means that the agent determines its **satisfaction**. A measure to express this satisfaction should meet two requirements. First, it should be a generic measure and therefore independent of the number of cells in the study area. Second, it should take into account the fact that a high probability of being assigned a cell should be valued more if it concerns a cell that was claimed strong than if it would concern a weakly claimed cell. Consequently, the satisfaction is determined by using the following equation:

$$S_x^t = \frac{\sum_{i=1}^{I}\sum_{j=1}^{J}\left(P\left(C_{ij,x}^{s,t}=1\right)\times P\left(A_{ij,x}^{t}=1\right)\right)}{\sum_{i=1}^{I}\sum_{j=1}^{J}P\left(C_{ij,x}^{s,t}=1\right)} \tag{14}$$

where $P\left(C_{ij,x}^{s,t}=1\right)$ is the "probability of claiming" as expressed by agent x for cell *(i,j)*, and $P\left(A_{ij,x}^{t}=1\right)$ is the "probability of assignment" that is suggested to agent x. The former probabilities are functioning as weights to the latter, resulting in a value between 0 and 1. This outcome is judged against the critical minimum satisfaction defined by the agent, S_{min}. When $S_x \geq S_{min}$, the *Assignments* as a whole – for the whole study area – are accepted. When $S_x < S_{min}$, the Participant does not accept and defines new *Claims* based on an adjusted strategy, i.e. a more democratic strategy (see 3.3.1). It should be noted that this is under the condition that the agent can still define a strategy that is (i) more democratic ánd (ii) leading to sufficient satisfaction when it would be fully granted. If not, the Participant rejects the *Assignments*. Thus, the reply the Initiator receives after a Participant's

[3] This is possible due to the fact that believed goal states, *Bel{GS}*, and Claims have the same format. They differ in the sense that the former are non-strategic expressions.

evaluation of the suggested *Assignments* is either the message “accepted”, new *Claims*, or the message “rejected”.[4]

4. INTERACTION PROTOCOLS

For organizing the process of generating plan proposals two basically distinctive interaction protocols are presented, both based on the Initiator-Participants principle: one agent initiating and managing the development of a plan proposal by requesting others to express their claims and integrating these claims into the plan proposal.

The protocols have an identical initialization round, as the Initiator will construct the initial believed study area future based on the task sizes as stated in the Plan Program. This collective belief becomes the starting point for the subsequent procedure in which the Initiator incrementally draws up the plan proposal from the various *Claims* it receives. It is for the way of requesting and processing the *Claims* that the Initiator can choose a specific protocol.

In general, convergence is established by organizing the negotiation between Initiator and Participants as an iterative process in which both parties consider adjustment of their strategies, and thus their decisions, in order to try to find mutually accepted solutions. Moreover, the Initiator applies an entropy-minimizing rule associated with its *Assignments* to ensure that, if the plan proposal evolves over several rounds or iterations, every new *Bel{SAF}* shows less entropy than the previous *Bel{SAF}*.

4.1 Simultaneous contributions

When the Initiator decides to simultaneously incorporate the *Claims* for the different land-uses into the plan proposal, the process is as follows:

1. The Initiator sends the currently believed study area future, *Bel{SAF}*, to all involved Participants at once, requesting their *Claims*.
2. Every Participant constructs its believed goal state, *Bel{GS}*, decides about its strategy on how to combine this belief with the given *Bel{SAF}*, and sends its resulting *Claims* back to the Initiator.
3. Having received the *Claims* of all Participants, the Initiator judges them strategically in order to determine its *Assignments* for the whole study area and for all land-uses. These *Assignments* are suggested to the Participants.

[4] The message “rejected” is not (necessarily) causing a dead-end in the process because the Initiator can also adjust its strategy, and accordingly its *Assignments*. As such, both parties can do effort to reach agreement.

4. Every Participant determines its satisfaction regarding the suggested *Assignments*. When *not* sufficiently satisfied, a Participant goes back to step 2 to choose a more democratic strategy, resulting in new *Claims*.[5] If there is no such strategy at hand that could have a satisfactory outcome, the message "rejected" is returned to the Initiator and control returns to step 3 where the Initiator can choose a more compliant strategy, resulting in new *Assignments*. When satisfied after one or more iterations, the agent replies to the Initiator with the message "accepted".
5. The Initiator turns the accepted *Assignments* into a new *Bel{SAF}*. When this belief still contains values other than zero and one, the Initiator proceeds with step 1, using the new *Bel{SAF}* as input. Otherwise the *Bel{SAF}* is turned into the final ***plan proposal***, and the process is successfully finished.

4.2 Sequential contributions

Alternatively, the Initiator can decide to incorporate the *Claims* of Participants sequentially. The process is then as follows:

1. The Initiator sending the initial believed study area future, *Bel{SAF}*, to all Participants and requests them to express their initial believed goal states, *Bel{GS}*.
2. Every Participant constructs its believed goal state, *Bel{GS}*, and sends it back to the Initiator.
3. The Initiator determines an **order-of-turns** based on how, at that time, it values the importance of the different remaining contributions from the viewpoint of its own land-use.[6]
4. The Initiator identifies the **agent-at-turn** and sends the current *Bel{SAF}* to that agent, requesting its claims.
5. The agent-at-turn updates its *Bel{GS}*, chooses a strategy on how to combine this belief with the *Bel{SAF}*, and sends its resulting *Claims* to the Initiator.
6. The Initiator chooses a strategy on to what extent to follow these *Claims*, and suggests the resulting *Assignments* to the agent-at-turn.
7. The agent-at-turn evaluates the suggested *Assignments* by determining its satisfaction. If not sufficiently satisfied the agent goes back to step 5 to choose a more democratic strategy, resulting in new *Claims*.[7] If there is

[5] In reaction to re-defined *Claims* the Initiator can redefine its *Assignments* by choosing a more compliant strategy in order to increase the chance that the Participant will be sufficiently satisfied.

[6] The Initiator by default judges its own contribution as most important, and therefore always takes first turn.

[7] See footnote 5.

no such strategy at hand that could have a satisfactory outcome, the message “rejected” is returned to the Initiator and control returns to step 6 where the Initiator can choose a more compliant strategy, resulting in new *Assignments*. When the agent-at-turn is satisfied after one or more iterations, the message “accepted” is returned to the Initiator.

8. The Initiator turns the accepted *Assignments* into a new *Bel{SAF}*. When this belief still contains values other than zero and one, it means that there are still agents that are not yet requested to express their claims, and hence the Initiator goes back to step 3, re-determines the order of turns and uses the new *Bel{SAF}* as input for the next agent-at-turn. Otherwise the *Bel{SAF}* is turned into the final ***plan proposal***, and the process is successfully finished.

5. CONCLUSIONS AND DISCUSSION

This paper elaborates on earlier work regarding the MASQUE multi-agent framework for generating alternative plans in local land-use planning. In this framework the agents represent land-use experts and initiate the development of plan proposals and request each other to express their claims in order to incrementally draw up these proposals. A probabilistic approach is presented that enables the agents to make decisions under uncertainty. Agents use both personal and collective beliefs in order to strategically choose their actions. Negotiation takes place between the initiating agent and the others in order to reach agreement on the incorporation of their claims, and is organized as an iterative process in which both parties consider conciliatory adjustments of their strategies, and thus their decisions, in order to try to find mutually accepted solutions. The probabilistic approach, in combination with the applied anthropomorphic definition of agents, is expected to result in an intelligent, flexible and comprehensible decision-support tool.

The framework will be implemented in a Java program to proof the validity of the concepts. We intend to report on this validation and further enhancements to the framework in future publications.

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