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ADAPTIVE REINFORCEMENT LEARNING OF MULTI-AGENT ETHICALLY-ALIGNED BEHAVIOURS: THE QSOM AND QDSOM ALGORITHMS

A PREPRINT

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ABSTRACT

The numerous deployed Artificial Intelligence systems need to be aligned with our ethical considerations. However, such ethical considerations might change as time passes: our society is not fixed, and our social mores evolve. This makes it difficult for these AI systems; in the Machine Ethics field especially, it has remained an under-studied challenge. In this paper, we present two algorithms, named QSOM and QDSOM, which are able to adapt to changes in the environment, and especially in the reward function, which represents the ethical considerations that we want these systems to be aligned with. They associate the well-known Q-Table to (Dynamic) Self-Organizing Maps to handle the continuous and multi-dimensional state and action spaces. We evaluate them on a use-case of multi-agent energy repartition within a small Smart Grid neighborhood, and prove their ability to adapt, and their higher performance compared to baseline Reinforcement Learning algorithms.

Keywords Machine Ethics • Artificial Moral Agents • Multi-Agent Systems • Reinforcement Learning • Multi-Agent Reinforcement Learning

1 Introduction

With the increasing deployment of systems using Artificial Intelligence (AI) techniques, questions are being raised within civil society and the scientific community about their impact on our lives. One of the most pressing questions is that of value alignment (Dignum 2019 ; World Economic Forum 2015): how can we ensure that these systems act in line with the moral values that are important to us? The field of Machine Ethics has proposed numerous approaches, based on a variety of techniques, from symbolic implementation to machine learning. However, the property of Continual

Learning, which we believe is important, has not been studied enough. Continual Learning concerns the ability of artificial agents to learn continuously and therefore to change their behaviour as a function of the environment. This is a particularly critical property in Machine Ethics, because ethics are not fixed: our currently accepted social mores evolve over time. In this paper, we propose in Section 3 two reinforcement learning algorithms, QSOM and QDSOM, that can adapt to changes in the reward function, representing these “changes in ethics”. These algorithms are then evaluated on an application case of multi-agent energy repartition within a small Smart Grid, described in Section 4. A discussion of their advantages and drawbacks is finally presented in Section 5.

2 State of the Art

In this section, we introduce the necessary knowledge, and explore the state of the art in the fields related to our work: *Machine Ethics* and *(Multi-Agent) Reinforcement Learning*. This exploration allows us to compare the existing approaches, their advantages, but also their limitations, and to define some concepts necessary to the understanding of our work.

2.1 Machine Ethics

The field of Machine Ethics is relatively recent among the other fields of Artificial Intelligence. A book published in 2011 gathers different essays on the nature of *Machine Ethics*, its importance, the difficulties and challenges to be solved, and also a few first approaches (Anderson and Anderson 2011). This book defines this new field of research:

The new field of machine ethics is concerned with giving machines ethical principles, or a procedure for discovering a way to resolve the ethical dilemmas we might encounter, enabling them to function in an ethically responsible manner through their own ethical decision making. (Anderson and Anderson 2011)

Being a recent field, several articles have sought to position themselves, or to offer a philosophical background. For example, Moor (2009) proposes a definition of what might be an “ethical robot”, and differentiates 4 different kinds of robots, ranging from those with the least ethical considerations to those which have near-human ethical reasoning abilities: *ethical impact agents*, *implicit ethical agents*, *explicit ethical agents*, and *full ethical agents*. The goal, for Machine Ethics designers and researchers, is to attain *explicit* ethical agents, as it is still unsure whether artificial *full* ethical agents can be built.

In the following, we briefly list a few approaches, and present a set of “properties” that we argue are important to design such ethical agents.

Discrete or continuous domains. In order to implement ethical considerations into an artificial agent, these considerations must be represented. This includes, e.g., data about the current situation, and the potential actions or decisions that are available to the agent. The choice of this representation must allow both for use-case richness, and for the agent’s ability to correctly use these representations. Two types of representations are commonly used: either *discrete* domains, which use a discrete set of symbols and discrete numbers, or *continuous* domains, which use continuous numbers that lead to an infinite set of symbols.

So far, discrete domains seem prevalent in *Machine Ethics*. For example, the emblematic Trolley Dilemma (Foot 1967) describes a situation where an uncontrolled trolley is driving on tracks towards a group of 5 persons. These persons, depending on the exact specification, are either unaware of the trolley, or unable to move. An agent may save this group by pulling up a lever, which would derail the trolley towards a single person. It can be seen that the representation of both the situation and the available actions are discrete in this dilemma: 2 actions are proposed, *pull the lever* or *do nothing*, and on the tracks are present 1 and 5 persons, respectively.

Similarly, the now defunct [DilemmaZ database](#) listed a plethora of moral dilemmas, proposed by the community, of which many apply to Artificial Intelligence and IT systems in general, e.g., smart homes, robots. Although a formal description of these dilemmas is not available, most of the natural language descriptions seem to imply discrete features. This is particularly clear for the definition of actions; for example, the “Smart home - Someone smoking marijuana in a house” dilemma, by Louise A. Dennis, offers the following 3 actions: “a) do nothing, b) alert the adults and let them handle the situation or c) alert the police”.

A final example is the *Moral Gridworlds* idea of Haas (2020) to train a Reinforcement Learning agent “to attribute subjective rewards and values to certain ‘moral’ actions, states of affairs, commodities, and perhaps even abstract representations”. Moral Gridworlds are based on gridworlds, which represent the environment as a 2-dimensional grid of cells. A RL agent is placed in one of these cells, and may either act in its cell, or move to one of the adjacent cells. Again, the environment uses discrete features, both for perception, i.e., a discrete set of cells, and for actions, i.e., either act, move up, left, right, or down.

Perhaps the ubiquitous use of discrete representations in Machine Ethics can be at least partially explained by their simplicity of usage within AI techniques. These “discrete dilemmas” are important, because they may very well happen one day in our society. We need systems that are able to make the best decision, with respect to our moral values, in such situations.

However, there are other situations that cannot be easily described by discrete representations. For example, foretelling the Smart Grid use-case that we describe in Section 4, when considering an energy distribution system, we may transition from a closed question “Should the agent consume energy? yes/no” to a more open question “What power should the agent request during a given time step?”. Arguably, such an action could be represented as a discrete set, by *discretizing* the continuous domain into a set, e.g., $\{0\text{Wh}, 1\text{Wh}, \dots, 1000\text{Wh}\}$, which contains 1001 actions. But this solution is harder to leverage when considering multi-dimensional domains: in addition to “how much energy should it consume”, we may also ask “What power should the agent buy?”. In this case, discretizing the continuous and multi-dimensional domain would result in a combinatorial explosion. The set of discrete actions may be represented as $\{(0\text{Wh}, 0\text{Wh}), (0\text{Wh}, 1\text{Wh}), (1\text{Wh}, 0\text{Wh}), (1\text{Wh}, 1\text{Wh}), \dots, (1000\text{Wh}, 1000\text{Wh})\}$, which contains 1001×1001 different actions, where each action is represented as a pair (consumed, bought). We already see, on 2 dimensions and with a grain of 1Wh, that a million actions would require too much time and computational resources to explore and analyze, in order to find the best one. The same argument can be made for perceptions as well: for example, instead of having a perception “the situation is fair”, or “the situation is unfair”, we may want to have an indicator of how fair the situation is, e.g., through well-known measures such as the Gini index, which is a real number comprised between 0 (perfect equality) and 1 (perfect inequality) (Gini 1936).

Such situations, which imply a large, continuous and multi-dimensional domain, are as likely to happen in our society as the discrete ones.

Mono- or Multi-agent.

According to a survey (Yu et al. 2018), many works consider a single agent isolated in its environment. This is the case, to give some examples, of GenEth (Anderson, Anderson, and Berenz 2018), or the *ethics shaping* technique (Wu and Lin 2018). Other approaches, such as Ethicaa (Cointe, Bonnet, and Boissier 2016), use multiple agents, which take actions and have an impact in a common, shared environment.

As Murukannaiah et al. (2020) put it:

Ethics is inherently a multiagent concern — an amalgam of (1) one party’s concern for another and (2) a notion of justice.

In Ethicaa (Cointe, Bonnet, and Boissier 2016), a judgment process is defined to allow agents to both 1) select the best ethical action that they should make, and 2) judge the behaviour of other agents so as to determine whether they can be deemed as “ethical”, with respect to one’s own preferences and upheld moral values. One long-term objective of this second point can be to define and compute a trust indicator for other agents; if an agent acts ethically, we may trust it. This raises an interesting rationale for exploring Machine Ethics in Multi-Agent Systems: even if we manage to somehow create a full ethical agent, which is guaranteed to take moral values and ethical stakes into account, it will have to work with other agents. We cannot guarantee that these agents will follow the same ethical preferences, nor even that they will consider ethical stakes at all. Our own agent must therefore take this into account.

Based on the previous reasons, we argue that the multi-agent case is important. Indeed, it corresponds to a more realistic situation: such artificial agents are bound to be included in our society, and thus to have to interact with other agents, whether artificial or human, or at least to live in an environment impacted by these other agents, and not in a perfectly isolated world. The question of the impact of other agents on an agent’s decision-making is thus of primary importance.

Top-Down, Bottom-Up, and Hybrid approaches.

Approach type is probably the most discussed property in *Machine Ethics*. It characterizes the way designers implement ethical considerations into artificial agents. Similarly to the usual classification in AI, works are divided into 3 categories (Allen, Smit, and Wallach 2005): *Top-Down*, *Bottom-Up*, and *Hybrid* approaches.

Top-Down approaches are interested in formalizing existing ethical principles from moral philosophy, such as Kant’s Categorical Imperative, or Aquinas’ Doctrine of Double Effect. The underlying idea is that, if these moral theories could be transformed into an algorithm that agents could follow to the letter, surely these agents’ behaviour would be deemed as ethical by human observers.

This formalization is often done through symbolic representation and reasoning, e.g., through logic, rules-based techniques, or even ontologies. Reasoning over these symbolic representations can rely upon expert knowledge, a priori injected. They also offer a better readability, of both the injected knowledge, and the resulting behaviour.

One of the advantages of Top-Down approaches is this ability to leverage such existing ethical principles from moral philosophy. Intuitively, it seems indeed better to rely on theories proposed by moral philosophers, which have been tested and improved over time.

Another advantage, emphasized by the work of Bremner et al. (2019), is the ability to use formal verification to ensure that agents' behaviours stay within the limits of the specified rules. To do so, the *Ethical Layer* they propose includes a planning module that creates plans, i.e., sequences of actions, and an ethical decision module to evaluate the plans, prevent unethical ones, and proactively ask for new plans if necessary. This formal verification ability is an important strength, as there are worries about agents malfunctioning. An agent that could be formally verified to stay within its bounds, could be said to be "ethical", with respect to the chosen ethical principle or theory.

However, there are some weaknesses to *Top-Down* approaches. For example, conflicts between different rules may arise: a simple conflict could be, for example, between the "Thou shalt not kill" rule, and another "You may kill only to defend yourself". The second one should clearly define when it is allowed to take precedence over the first one. A more complicated conflict would be two rules that commend different, non-compatible actions. For example, let us imagine two missiles attacking two different buildings in our country: the first one is a hospital, the second one is a strategic, military building, hosting our defense tools. An autonomous drone can intercept and destroy one of the two missiles, but not the two of them; which one should be chosen? A rule may tell us to protect human lives, whereas another encourages us to defend our arsenal, in order to be able to continue protecting our country. These two rules are not intrinsically in conflict, unlike our previous example: we would like to follow both of them, and to destroy the two missiles. Unfortunately, we are physically constrained, and we must make a choice. Thus, a rule has to be preferred to the other.

Ethicaa (Cointe, Bonnet, and Boissier 2016) agents make a distinction between the moral values and ethical principles, and they consider multiple ethical principles. Each ethical principle determines whether an action is ethical, based on the permissible and moral evaluations. Multiple actions can thus be evaluated as ethical by the ethical principles, and, in many cases, there is no single action satisfying all ethical principles. To solve this issue, agents also include a priority order over the set of ethical principles known to them. In this way, after an agent determines the possible, moral, and ethical actions, it can choose an action, even if some of its rules disagree and commend different actions. To do so, they filter out the actions that are not evaluated as ethical, and thus should not be selected, by their most preferred ethical principle, according to the ethical priority order. As long as multiple actions remain considered, they move on to the next preferred ethical principle, and so on, until a single action remains.

Finally, another drawback is the lack of adaptability of these approaches. Indeed, due to their explicit but fixed knowledge base, they cannot adapt to an unknown situation, or to an evolution of the ethical consensus within the society. We argue that this capability to adapt is particularly important. It is similar to what Nallur (2020) calls the *Continuous Learning* property:

Any autonomous system that is long-lived must adapt itself to the humans it interacts with. All social mores are subject to change, and what is considered ethical behaviour may itself change.

We further note that, in his landscape, only 1 out of 10 considered approaches possesses this ability (Nallur 2020, Table 2).

Bottom-Up approaches try to learn a behaviour through experience, e.g., from a dataset of labeled samples, or trial and error interactions.

For example, GenEth (Anderson, Anderson, and Berenz 2018) uses ethicists' decisions in multiple situations as a dataset representing the ethical considerations that should be embedded in the agent. This dataset is leveraged through Inductive Logic Programming (ILP) to learn a logical formula that effectively drives the agent's behaviour, by determining the action to be taken in each situation. ILP allows creating a logical formula sufficiently generic to be applied to other situations, not encountered in the dataset. An advantage of this approach is that it learns directly from ethicists' decisions, without having to program it by hand. The resulting formula may potentially be understandable, provided that it is not too complex, e.g., composed of too many terms or terms that in themselves are difficult to understand.

Another approach proposes to use Reinforcement Learning RL (Wu and Lin 2018). Reinforcement Learning relies on rewards to reinforce, or on contrary, to mitigate a given behaviour. Traditionally, rewards are computed based on the task we wish to solve. In the work of Wu and Lin (2018), an ethical component is added to the reward, in the form of a difference between the agent's behaviour, and the behaviour of an average human, obtained through a dataset of behaviours, and supposedly exhibiting ethical considerations. The final reward, which is sent to agents, is computed as the sum of the "task" reward, and the "ethical" reward. Agents thus learn to solve their task, while exhibiting the ethical considerations that are encoded in the human samples. One advantage of this approach is that the "ethical" part of the behaviour is mostly task-agnostic. Thus, only the task-specific component of the reward has to be crafted by designers

for a new task. Nevertheless, one may wonder to which extent does this dataset really exhibit ethical considerations? We humans do not always respect laws or moral values, e.g., we sometimes drive too fast, risking others' lives, or we act out of spite, jealousy, etc. To determine whether this dataset is appropriate, an external observer, e.g., a regulator, an ethicist, or even a concerned citizen, has to look at its content, and understand the data points.

These 2 approaches, although based on learning, have not considered the question of long-term adaptation to changing situations and ethical mores. Indeed, if the current society norms with regard to ethics change, these agents' behaviours will have to change as well. It will probably require to create a new dataset, and to learn the agents again, from scratch, on these new data.

Moreover, Bottom-Up approaches are harder to interpret than Top-Down ones. For example, a human regulator or observer, willing to understand the expected behaviour, will have to look at the dataset, which might be a tedious task and difficult to apprehend, because of both its structure and the quantity of data. This is all the more true with Deep Learning approaches, which require an enormous amount of data (Marcus 2018), making datasets exploration even more daunting.

Finally, Hybrid approaches combine both Top-Down and Bottom-Up, such that agents are able to learn ethical behaviours by experience, while being guided by an existing ethical framework to enforce constraints and prevent them from diverging. As Dignum (2019) points out:

By definition, hybrid approaches have the potential to exploit the positive aspects of the top-down and bottom-up approaches while avoiding their problems. As such, these may give a suitable way forward. (Dignum 2019, 81)

One of such hybrid works is the approach by Honarvar and Ghasem-Aghaee (2009) to combine BDI agents with Case-based Reasoning and an Artificial Neural Network. Faced with a given situation, the agent proposes an action to perform, and then searches its database of already known cases for similar situations and similar actions. If a close enough case is found, and the action was considered as ethical in this case, the action is taken. However, if in this close enough case, the action was considered as unethical, a new action is requested, and the agent repeats the same algorithm. If the agent does not have a sufficiently close case, it performs the action, and uses its neural network to evaluate the action's consequences and determine whether it was effectively aligned with the ethical considerations. This evaluation is memorized in the case database, to be potentially reused during the next decision step. This approach indeed combines both reasoning and learning capabilities; however, it may be difficult to apply. Case-based reasoning allows grouping close situations and actions, but requires to specify how to group them, i.e., what is the distance function, and how to adapt an evaluation when either the situation or the action differs. For example, let us assume that, in a situation s , the agent's action was to consume 500Wh of energy, and the action was evaluated as ethical. In a new situation, s' , which is deemed as similar to s by the case-based reasoner, another action is proposed, which is to consume 600Wh. Is this action ethical? How can we translate the difference between 600 and 500 in terms of ethical impact? This requires specifying an "adaptation knowledge" that provides the necessary knowledge and tools.

Still, Hybrid approaches offer the possibility of learning a behaviour, thus adapting to any change in the environment, while still guiding or constraining the agent through symbolic reasoning and knowledge, thus injecting domain expert knowledge, more easily understandable and modifiable than datasets of examples.

2.2 Reinforcement Learning

We propose to use Reinforcement Learning (RL) as a method to learn behaviours aligned with moral values, and provide here the background knowledge and concepts that are necessary to understand the rest of the paper. We detail motivations for using RL, definitions of core concepts, and equations.

RL is a method to learn a behaviour, mainly by using trial-and-error. Sutton and Barto (2018) define it as follows:

Reinforcement learning problems involve learning what to do — how to map situations to actions — so as to maximize a numerical reward signal. (Sutton and Barto 2018, 2)

To do so, learning agents are placed in a closed-loop with an environment, with which they interact. Through the environment, they have knowledge of which state they are in, and they take actions to change the state. One of the key points of RL is that learning agents are not told which action is the correct one; the feedback they receive, or *reward*, merely tells them to which degree the action was satisfying. Learning agents must discover the best action, i.e., the one that yields the highest reward, by accumulating enough experience, that is by repetitively trying each action in each situation, and observing the received rewards.

As we mentioned, RL agents receive feedback, which differentiates them from the *unsupervised* paradigm. However, unlike the *supervised* paradigm, this feedback does not clearly indicate which was the correct answer. This removes the

assumption that we know the correct answer to each input. Instead, we provide a reward function, and thus optimize the agent’s output step by step, by improving the proposed action based on the reward.

The goal of a RL algorithm is to learn a policy, or strategy, denoted π , such that the agent knows which action to take in each situation. π is often defined as $\pi : \mathbb{S} \rightarrow \mathbb{A}$ in the case of a *deterministic* policy, where \mathbb{S} is the space of possible states, and \mathbb{A} the space of possible actions. To each state s is associated a single action $\pi(s) = a$, which the agent should take in order to maximize its reward. Another formulation is $\pi : \mathbb{S} \times \mathbb{A} \rightarrow [0, 1]$, in the case of a *stochastic* policy. For each combination of state-action (s, a) is associated a probability $\pi(s, a)$ of taking action a in the state s , such that $\forall s \in \mathbb{S} : \sum_{\forall a \in \mathbb{A}} \pi(s, a) = 1$.

There are several challenges in RL, of which one of the most known and perhaps important is the *exploration-exploitation trade-off*. In order to facilitate learning the policy function, RL researchers often rely on the notion of *values*¹, in aptly-named *value-based* methods, such as the well-known Q-Learning (Watkins and Dayan 1992). The value of a state, or a state-action pair, represents the long-term interest of being in this state, whereas the reward is short-term feedback. The agent could receive a high reward for taking an action a in a state s , but ending up in a state s' in which only low rewards can be obtained. In this case, we will say that the value of state s' , denoted as $V(s')$ is low. By extension, the agent has little interest in performing action a while in state s , since it will lead it to a low-interest state.

In the previous paragraph, we derived the interest of action a , in a state s , from the value $V(s')$ which it leads to. It is also possible to learn directly the value of state-action pairs, which is the main idea of the Q-Learning algorithm. To retain the different interests of all state-action pairs, a table, named the *Q-Table*, is created, having the states as columns and actions as rows. The *Q-Value* $Q(s, a)$ is thus defined as the interest of the state-action pair (s, a) , i.e., the interest of taking action a in state s . Additionally, the value of a state as a whole is defined as $V(s) = \max_a Q(s, a)$.

Based on these definitions, the agent is able to learn the Q-Table by iteratively collecting experiences from the environment, in the form of $\langle s, a, s', r \rangle$ tuples, updating the interest $Q(s, a)$ based on both the short-term reward r , and the long-term interest $V(s')$ of arriving in state s' . Mathematically, this can be solved through dynamic programming, by applying the Bellman equation on the Q-Values (Bellman 1966):

$$Q_{t+1}(s_t, a_t) \leftarrow \alpha \left[r_t + \gamma \max_{a'} Q_t(s_{t+1}, a') \right] + (1 - \alpha) Q_t(s_t, a_t) \tag{1}$$

Where r_t was the reward received at step t , s_t was the state at step t , a_t was the action chosen by the agent, and s_{t+1} is the new state resulting from performing a_t in s_t .

As the values are updated by taking the difference between the old value and a new value, this type of methods is named the *Temporal Difference* learning, or TD-Learning.

2.3 Multi-Agent Reinforcement Learning

Although Reinforcement Learning was originally concerned with the learning of a single agent, there are numerous cases where a multi-agent system can, or must, be considered.

For example, let us consider a virtual agent dedicated to helping a human user in its day-to-day tasks, such as booking appointments. The diversity of human users implies a diversity of virtual agents, which will have to communicate and interact together, in order to solve the tasks of their users. In this example, the multiplicity of agents is a necessity that stems from the social system in which we live.

One of the most important challenges that additionally arises in multi-agent systems is the problem of “Multi-Agent Credit Assignment Problem” (MA-CAP). Several definitions of the MA-CAP have been given in the literature, which are all very similar. We particularly appreciate the formulation of Yliniemi and Tumer (2014) :

Each agent seeks to maximize its own reward; with a properly designed reward signal, the whole system will attain desirable behaviors. This is the science of credit assignment: determining the contribution each agent had to the system as a whole. Clearly quantifying this contribution on a per-agent level is essential to multiagent learning. (Yliniemi and Tumer 2014, 2)

The survey of Panait and Luke (2005, 8) summarizes several methods to assign rewards.

The *Global reward* approach considers the contribution of the whole team. Usually, the same reward is given to all agents, either by taking the sum of contributions, or by dividing the sum of contributions by the number of learners. In any case, a consequence is that *all* learners’ rewards depend on each agent. When an agent’s contribution decreases

¹We use value here in a different sense than the moral value used earlier. To avoid confusion, we will always specify *moral* value when referring to this first meaning.

(resp. increases), all learners see their reward decrease as well (resp. increase). This is a simple approach that intuitively fosters collaboration, since all agents need to perform well in order to receive a high reward.

However, this approach does not send accurate feedback to the learners. Let us consider a situation in which most agents have exhibited a good behaviour, although another one has failed to learn correctly, and has exhibited a rather bad (or uninteresting) behaviour. As the individual reward depends on the team’s efforts, the “bad” agent will still receive a praising reward. It will therefore have little incentive to change its behaviour. On the contrary, the “good” agents could have received a higher reward, if it were not for their “bad” colleague. Their behaviour does not necessarily need to change, however they will still try to improve it, since they expect to improve their received rewards.

At the opposite extreme, the *Local reward* approach considers solely the contribution of an individual agent to determine its reward. For example, if the agents’ task is to take waste to the bin, an agent’s reward will be the number of waste products that this specific agent brought. An advantage of this approach is to discourage laziness, as the agent cannot rely upon others to effectively achieve the task. By definition, agents receive a feedback that is truer to their actual contribution.

A problem of *local rewards* is that they incentivize greedy behaviours and do not always foster collaboration. Indeed, as agents are rewarded based on their own contribution, without taking the others into account, they have no reason to help other agents, or even to let them do their task. In the waste example, an agent could develop a stealing behaviour to take out more waste products. Another common example is the one of a narrow bridge that two agents must cross to achieve their task. They both arrive at the bridge at the same time, and none of them is willing to let the other one cross first, since that would reduce their own reward, or, phrased differently, would prevent them from getting an even higher reward. Thus, they are both stuck in a non-interesting situation, both in the collective and individual sense, due to their maximizing of the individual interest only.

Another method to determine an agent’s contribution to the team is to imagine an environment in which the agent had not acted. This method is sometimes called *Difference Rewards* (Yliniemi and Tumer 2014). The idea of this method is to reward agents if their contribution was helpful for the team, and to force a high impact of an agent’s action on its own reward. It is computed as follows:

$$D_i(z) = G(z) - G(z_{-i}) \tag{2}$$

where $D_i(z)$ is the reward of an agent i , based on the context z , which is both the state and the joint-action of all agents in the environment; $G(z)$ is the global reward for the context z , and $G(z_{-i})$ is an hypothetical reward, which would have been given to the team, if the agent i had not acted in the environment. In other words, if the current environment is better than the hypothetical one, this means the agent’s action has improved the environment. It should be rewarded positively so as to reinforce its good behaviour. As $G(z) > G(z_{-i})$, the reward will effectively be positive. Conversely, if the current environment is worse than the hypothetical one, this means the agent’s action has deteriorated the environment, or contributed negatively. The agent should therefore receive a negative reward, or punishment, in order to improve its behaviour. In this case, as $G(z) < G(z_{-i})$, the result will be negative. If the agent did not contribute much, its reward will be low, to encourage it to participate more, although without impairing the team’s effort, as in the bridge example. Otherwise, the global reward $G(z)$ would diminish, and the agent’s reward would therefore decrease as well. Finally, it can be noted that the other agents’ actions have a low impact on an agent reward.

3 The QSOM and QDSOM algorithms

As stated in the State of the Art, the algorithms that we propose need to handle continuous and multi-dimensional state-action spaces. They are based on an existing work (Smith 2002a, 2002b) that we extend and evaluate in a more complex use-case. Smith’s initial work proposed, in order to handle such domains, to associate Self-Organizing Maps (SOMs) to a Q-Table.

We first briefly explain what is a Q-Table from the Q-Learning algorithm, and its limitations. We then present Self-Organizing Maps, the Dynamic Self-Organizing Map variation, and how we can use them to solve the Q-Table’s limitations. We combine these components to propose an extension of Smith’s algorithm that we name *QSOM*, which leverages a Q-Table and Self-Organizing Maps (SOMs), and a new algorithm named *QDSOM*, which leverages a Q-Table and Dynamic SOMs (DSOMs).

Figure 1 presents a summarizing schema of our proposed algorithms. It includes multiple learning agents that live within a shared environment. This environment sends observations to agents, which represent the current state, so that agents may choose an action and perform it in the environment. In response, the environment changes its state, and sends them new observations, potentially different for each agent, corresponding to this new state, as well as a reward indicating how correct the performed action was. Learning agents leverage the new observations and the reward

to update their internal model. This observation-action-reward cycle is then repeated so as to make learning agents improve their behaviour, with respect to the considerations embedded in the reward function. The decision process relies on 3 structures, a State (Dynamic) Self-Organizing Map, also named the State-(D)SOM, an Action (Dynamic) Self-Organizing Map, also named the Action-(D)SOM, and a Q-Table. They take observations as inputs and output an action, which are both vectors of continuous numbers. The learning process updates these same structures, and takes the reward as an input, in addition to observations.

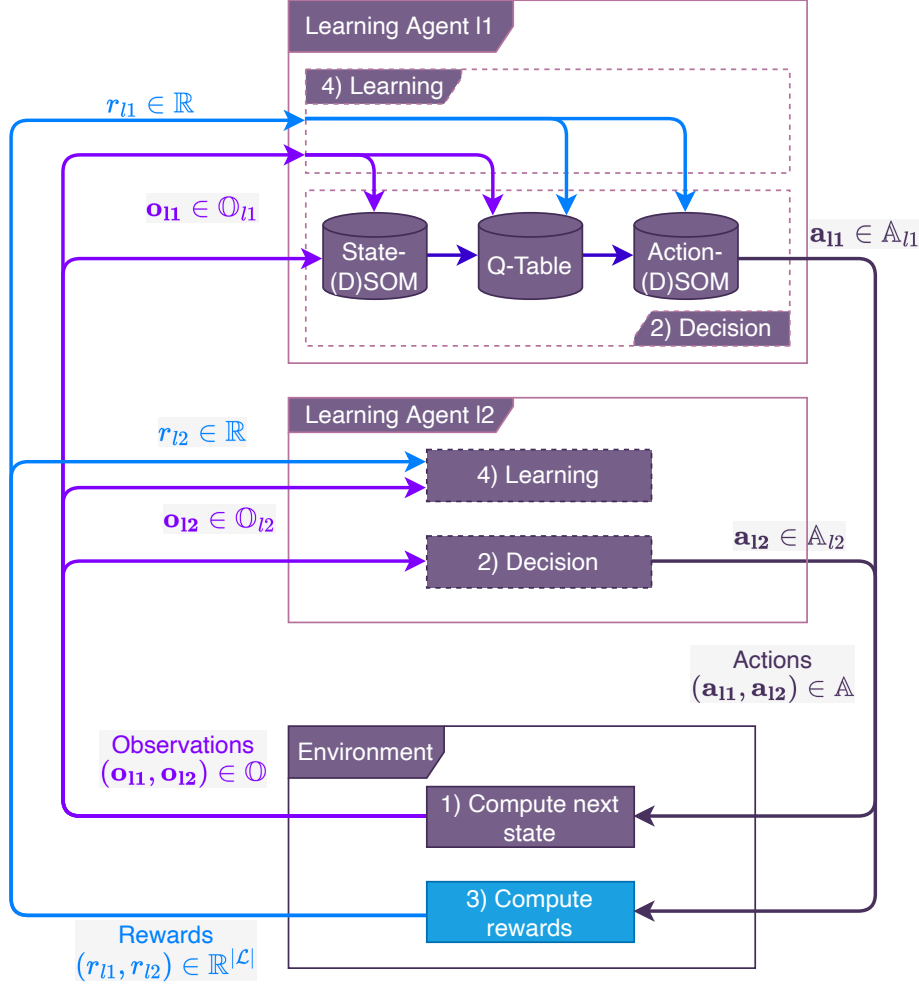


Figure 1: Architecture of the QSOM and QDSOM algorithms, which consist of a decision and learning processes. The processes rely on a State-(D)SOM, an Action-(D)SOM, and a Q-Table.

3.1 Q-Table

The *Q-Table* is the central component of the well-known Q-Learning algorithm (Watkins and Dayan 1992). It is tasked with learning the *interest* of a state-action pair, i.e., the expected horizon of received rewards for taking an action in a given state. The Q-Table is a tabular structure, where rows correspond to possible states, and columns to possible actions, such that the row $Q(s, \cdot)$ gives the interests of taking every possible action in state s , and, more specifically, the cell $Q(s, a)$ is the interest of taking action a in state s . These cells, also named *Q-Values*, can be learned iteratively by collecting experiences of interactions, and by applying the Bellman equation.

We recall that the interests take into account both the short-term immediate reward, but also the interest of the following state s' , resulting from the application of a in s . Thus, an action that leads to a state where any action yields a low reward, or in other word an unattractive state, would have a low interest, regardless of its immediate reward.

Assuming that the Q-Values have converged towards the “true” interests, the optimal policy can be easily obtained through the Q-Table, by selecting the action with the maximum interest in each state. By definition, this “best action” will lead to states with high interests as well, thus yielding, in the long-term, the maximum expected horizon of rewards.

An additional advantage of the Q-Table is the ability to directly have access to the interests, in comparison to other approaches, such as *Policy Gradient*, which typically manipulate actions’ probabilities, increasing and decreasing them based on received rewards. These interests can be conveyed to humans to support or detail the algorithm’s decision process, an advantage that could be exploited for explainability.

Nevertheless, Q-Tables have an intrinsic limitation: they are defined as a tabular structure. This structure works flawlessly in simple environments, e.g., those with a few discrete states and actions. Yet, in more complex environments, especially those that require continuous representations of states and actions, it is not sufficient any more, as it would require an infinite number of rows and columns, and therefore an infinite amount of memory. Additionally, because of the continuous domains’ nature, it would be almost impossible to obtain twice the exact same state: the cells, or Q-Values, would almost always get at most a single interaction, which does not allow for adequate learning and convergence towards the true interests.

To counter this disadvantage, we rely on the use of Self-Organizing Maps (SOMs) that handle the continuous domains. The mechanisms of SOMs are explained in the next section, and we detail how they are used in conjunction with a Q-Table in Section 3.3.

3.2 (Dynamic) Self-Organizing Maps

A Self-Organizing Map (SOM) (Kohonen 1990) is an artificial neural network that can be used for unsupervised learning of representations for high-dimensional data. SOMs contain a fixed set of neurons, typically arranged in a rectangular 2D grid, which are associated to a unique identifier, e.g., neuron #1, neuron #2, etc., and a vector, named the *prototype vector*. Prototype vectors lie in the latent space, which is the highly dimensional space the SOM must learn to represent.

The goal is to learn to represent as closely as possible the distribution of data within the latent space, based on the input data set. To do so, prototype vectors are incrementally updated and “moved” towards the different regions of the latent space that contain the most data points. Each time an input vector, or data point, is presented to the map, the neurons compete for attention: the one with the closest prototype vector to the input vector is named the *Best Matching Unit* (BMU). Neurons’ prototypes are then updated, based on their distance to the BMU and the input vector. By doing this, the neurons that are the closest to the input vector are moved towards it, whereas the farthest neurons receive little to no modification, and thus can focus on representing different parts of the latent space.

As the number of presented data points increases, the distortion, i.e., the distance between each data point and its closest prototype, diminishes. In other words, neurons’ prototypes are increasingly closer to the real (unknown) distribution of data.

When the map is sufficiently learned, it can be used to perform a mapping of high dimensional data points into a space of lower dimension. Each neuron represents the data points that are closest to its prototype vector. Conversely, each data point is represented by the neuron whose prototype is the closest to its own vector.

This property of SOMs allows us to handle continuous, and multi-dimensional state and action spaces.

Figure 2 summarizes and illustrates the training of a SOM. The blue shape represents the data distribution that we wish to learn, from a 2D space for easier visualization. Typically, data would live in higher dimension spaces. Within the data distribution, a white disc shows the data point that is presented to the SOM at the current iteration step. SOM neurons, represented by black nodes, and connected to their neighbors by black edges, are updated towards the current data point. Among them, the Best Matching Unit, identified by an opaque yellow disc, is the closest to the current data point, and as such receives the most important update. The closest neighbors of the BMU, belonging to the larger yellow transparent disc, are also slightly updated. Farther neurons are almost not updated. The learned SOM is represented on the right side of the figure, in which neurons correctly cover the data distribution.

The update received by a neuron is determined by Equation 3, with v being the index of the neuron, \mathbf{W}_v is the prototype vector of neuron v , \mathbf{D}_t is the data point presented to the SOM at step t . u is the index of the Best Matching Unit, i.e., the neuron that satisfies $u = \operatorname{argmin}_{v} \|\mathbf{D}_t - \mathbf{W}_v\|$.

$$\mathbf{W}_v^{t+1} \leftarrow \mathbf{W}_v^t + \theta(u, v, t) \alpha(t) (\mathbf{D}_t - \mathbf{W}_v^t) \quad (3)$$

In this equation, θ is the neighborhood function, which is typically a gaussian centered on the BMU (u), such that the BMU is the most updated, its closest neighbors are slightly updated, and farther neurons are not updated. The learning rate α , and the neighborhood function θ both depend on the time step t : they are often monotonically decreasing, in order to force neurons’ convergence and stability.

One of the numerous extensions of the Self-Organizing Map is the Dynamic Self-Organizing Map (DSOM) (Rougier and Boniface 2011). The idea behind DSOMs is that self-organization should offer both stability, when the input data

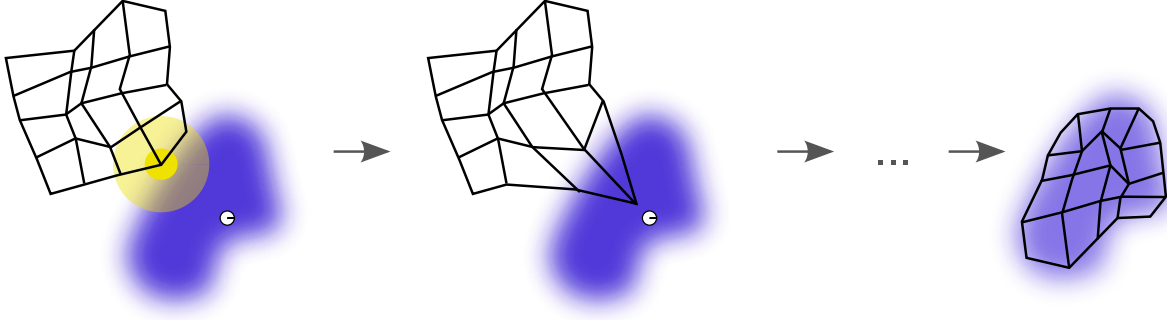


Figure 2: Training of a SOM, illustrated on several steps. Image extracted from [Wikipedia](#).

does not change much, and dynamism, when there is a sudden change. This stems from neurological inspiration, since the human brain is able to both stabilize after the early years of development, and dynamically re-organize itself and adapt when lesions occur.

As we mentioned, the SOM enforces stability through decreasing parameters (learning rate and neighborhood), however this also prevents dynamism. Indeed, as the parameters approach 0, the vectors’ updates become negligible, and the system does not adapt any more, even when faced with an abrupt change in the data distribution.

DSOMs propose to replace the time-dependent parameters by a time-invariant one, named the *elasticity*, which determines the coupling of neurons. Whereas SOMs and other similar algorithms try to learn the density of data, DSOMs focus on the structure of the data space, and the map will not try to place several neurons in a high-density region. In other words, if a neuron is considered as sufficiently close to the input data point, the DSOM will not update the other neurons, assuming that this region of the latent space is already quite well represented by this neuron. The “sufficiently close” is determined through the elasticity parameter: with high elasticity, neurons are tightly coupled with each other, whereas lower elasticity let neurons spread out over the whole latent space.

DSOMs replace the update equation with the following:

$$\mathbf{W}_i^{t+1} \leftarrow \alpha \|\mathbf{D}_t - \mathbf{W}_i^t\| h_\eta(i, u, \mathbf{D}_t) (\mathbf{D}_t - \mathbf{W}_i^t) \quad (4)$$

$$h_\eta(i, u, \mathbf{D}_t) = \exp\left(-\frac{1}{\eta^2} \frac{\|P(i) - P(u)\|^2}{\|\mathbf{D}_t - \mathbf{W}_u\|^2}\right) \quad (5)$$

where α is the learning rate, i is the index of the currently updated neuron, \mathbf{D}_t is the current data point, u is the index of the best matching unit, η is the elasticity parameter, h_η is the neighborhood function, and $P(i)$, $P(u)$ are respectively the positions of neurons i and u in the grid (not in the latent space). Intuitively, the distance between $P(i)$ and $P(u)$ is the minimal number of consecutive neighbors that form a path between i and u .

3.3 The learning and decision algorithms

We take inspiration from Decentralized Partially-Observable Markovian Decision Processes (DecPOMDPs) to formally describe our proposed algorithms. DecPOMDPs are an extension of the well-known Markovian Decision Process (MDP) that considers multiple agents taking repeated decisions in multiple states of an environment, by receiving only partial observations about the current state. In contrast with the original DecPOMDP as described by Bernstein (Bernstein et al. 2002), we explicitly define the set of learning agents, and we assume that agents receive (different) individual rewards, instead of a team reward.

Definition 1. A Decentralized Partially-Observable Markovian Decision Process is a tuple $\langle \mathcal{L}, \mathbb{S}, \mathbb{A}, T, \mathbb{O}, D, R, \gamma \rangle$, where:

- \mathcal{L} is the set of learning agents, of size $n = |\mathcal{L}|$.
- \mathbb{S} is the state space, i.e., the set of states that the environment can possibly be in. States are not directly accessible to learning agents.
- \mathbb{A}_l is the set of actions accessible to agent l , $\forall l \in \mathcal{L}$ as all agents take individual actions. We consider multi-dimensional and continuous actions, thus we have $\mathbb{A}_l \subseteq \mathbb{R}^d$, with d the number of dimensions, which depends on the case of application.

- \mathbb{A} is the action space, i.e., the set of joint-actions that can be taken at each time step. A joint-action is the combination of all agents’ actions, i.e., $\mathbb{A} = \mathbb{A}_{l_1} \times \dots \times \mathbb{A}_{l_n}$.
- T is the transition function, defined as $T: \mathbb{S} \times \mathbb{A} \times \mathbb{S} \rightarrow [0, 1]$. In other words, $T(s'|s, \mathbf{a})$ is the probability of obtaining state s' after taking the action \mathbf{a} in state s .
- \mathbb{O} is the observation space, i.e., the set of possible observations that agents can receive. An observation is a partial information about the current state. Similarly to actions, we define \mathbb{O}_l as the observation space for learning agent l , $\forall l \in \mathcal{L}$. As well as actions, observations are multi-dimensional and continuous, thus we have $\mathbb{O}_l \subseteq \mathbb{R}^g$, with g the number of dimensions, which depends on the use case.
- \mathcal{O} is the observation probability function, defined as $\mathcal{O}: \mathbb{O} \times \mathbb{S} \times \mathbb{A} \rightarrow [0, 1]$, i.e., $\mathcal{O}(\mathbf{o}|s', \mathbf{a})$ is the probability of receiving the observations \mathbf{o} after taking the action \mathbf{a} and arriving in state s' .
- R is the reward function, defined as $\forall l \in \mathcal{L} \quad R_l: \mathbb{S} \times \mathbb{A}_l \rightarrow \mathbb{R}$. Typically, the reward function itself will be the same for all agents, however, agents are rewarded individually, based on their own contribution to the environment through their action. In other words, $R_l(s, \mathbf{a}_l)$ is the reward that learning agent l receives for taking action \mathbf{a}_l in state s .
- γ is the discount factor, to allow for potentially infinite horizon of time steps, with $\gamma \in [0, 1]$.

The RL algorithm must learn a stochastic strategy π_l , defined as $\pi_l: \mathbb{O}_l \times \mathbb{A}_l \rightarrow [0, 1]$. In other words, given the observations \mathbf{o}_l received by an agent l , $\pi(\mathbf{o}_l, \mathbf{a})$ is the probability that agent l will take action \mathbf{a} .

We recall that observations and actions are vectors of floating numbers, the RL algorithm must therefore handle this accordingly. However, it was mentioned in Section 3.1 that the Q-Table is not suitable for continuous data. To solve this, we take inspiration from an existing work (Smith 2002a, 2002b) and propose to use variants of Self-Organizing Maps (SOMs) (Kohonen 1990).

We can leverage SOMs to learn to handle the observation and action spaces: neurons learn the topology of the latent space and create a discretization. By associating each neuron with a unique index, we are able to discretize the multi-dimensional data: each data point is recognized by the neuron with the closest prototype vector, and thus is represented by a discrete identifier, i.e., the neuron’s index.

The proposed algorithms are thus based on two (Dynamic) SOMs, a State-SOM, and an Action-SOM, which are associated to a Q-Table. To navigate the Q-Table and access the Q-Values, we use discrete identifiers obtained from the SOMs. The Q-Table’s dimensions thus depend on the (D)SOMs’ number of neurons: the Q-Table has exactly as many rows as the State-(D)SOM has neurons, and exactly as many columns as the Action-(D)SOM has neurons, such that each neuron is represented by a row or column, and reciprocally.

Our algorithms are separated into two distinct parts: the *decision* process, which chooses an action from received observations about the environment, and the *learning* process, which updates the algorithms’ data structures, so that the next decision step will yield a better action. We present in details these two parts below.

3.3.1 The decision process

We now explain the decision process that allows an agent to choose an action from received observations, which is described formally in Algorithm 1 and represented in Figure 3. First, we need to obtain a discrete identifier from an observation \mathbf{o} that is a vector $\in \mathbb{O}_l \subseteq \mathbb{R}^g$, in order to access the Q-Table. To do so, we look for the Best Matching Unit (BMU), i.e., the neuron whose prototype vector is the closest to the observations, from the State-SOM, which is the SOM tasked with learning the observation space. The unique index of the BMU is used as the state identifier s (line 9).

We call this identifier a “state hypothesis”, and we use it to navigate the Q-Table and obtain the expected interest of each action, assuming we have correctly identified the state. Knowing these interests $Q(s, \cdot)$ for all actions, we can assign a probability of taking each one, using a Boltzmann distribution (line 10). Boltzmann is a well-known and used method in RL that helps with the exploration-exploitation dilemma. Indeed, agents should try to maximize their expectancy of received rewards, which means they should *exploit* high-rewarding actions, i.e., those with a high interest. However, the true interest of the action is not known to agents: they have to discover it incrementally by trying actions into the environment, in various situations, and memorizing the associated reward. If they only choose the action with the maximum interest, they risk focusing on few actions, thus not exploring the others. By not sufficiently exploring, they maintain the phenomenon, as not explored actions will stay at a low interest, reducing their probability of being chosen, and so on. Using Boltzmann mitigates this problem, by giving similar probabilities to similar interests, and yet, a non-zero probability of being chosen even for actions with low interests.

The Boltzmann probability of an action j being selected is computed based on the action’s interest, in the current state, relatively to all other actions’ interests, as follows:

Algorithm 1 Decision algorithm

Data \mathcal{U} the neurons in the State-(D)SOM
 1: \mathbf{U}_i the vector associated to neuron i in the State-(D)SOM
 2: \mathcal{W} the neurons in the Action-(D)SOM
 3: \mathbf{W}_j the vector associated to neuron j in the Action-(D)SOM
 4: $Q(s, a)$ the Q-value of action a in state s
 5: τ the Boltzmann's temperature
 6: ϵ Noise control parameter
 7:
 8: **function** DECISION(Observations \mathbf{o})
 9: $s \leftarrow \operatorname{argmin}_{i \in \mathcal{U}} \|\mathbf{o} - \mathbf{U}_i\|$
 10: Let P be the Boltzmann distribution over the Q-Values. We draw a random variable X from P , and we denote the probability that X equals a given value j : $P(X = j)$.
 11: Draw $j \sim P(X = j) = \frac{\exp(\frac{Q(s,j)}{\tau})}{\sum_{k=1}^{|\mathcal{W}|} \frac{\exp(Q(s,k))}{\tau}}$
 12: Let \mathbf{W}_j be the chosen action's parameters
 13: **for** $k \in$ all dimensions of \mathbf{W}_j **do**
 14: $\text{noise} \sim \text{random}(\epsilon)$
 15: $W'_{j,k} \leftarrow W_{j,k} + \text{noise}$
 16: **end for**
 17: Return action $\mathbf{a} \leftarrow \mathbf{W}'_j$
 18: **end function**

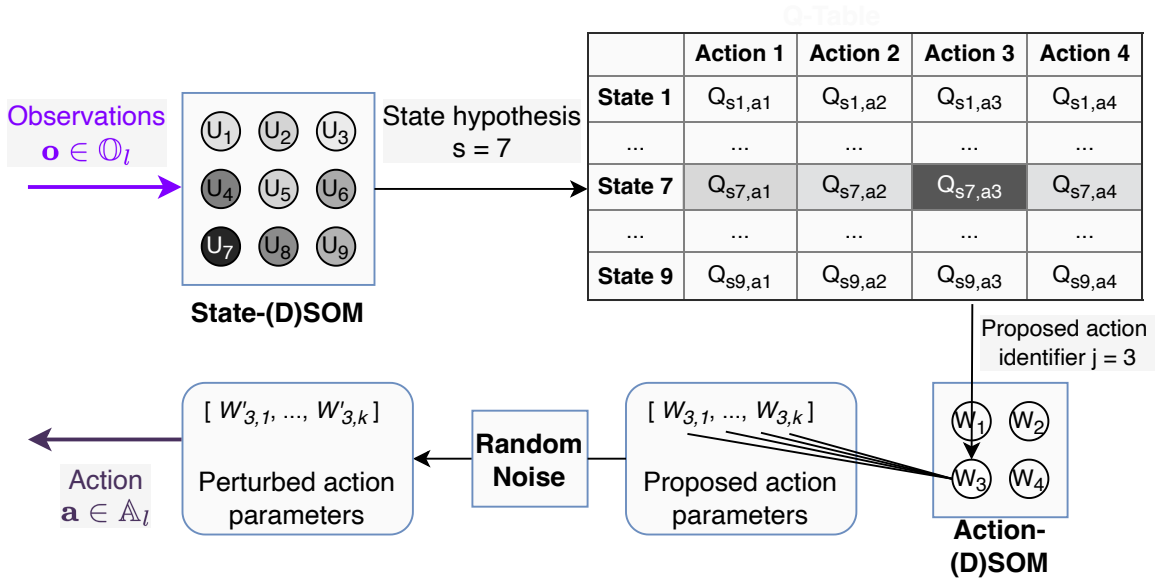


Figure 3: Dataflow of the Q-(D)SOM decision process.

$$P(X = j) = \frac{\frac{\exp(Q(s,j))}{\tau}}{\sum_{k=1}^{|\mathcal{W}|} \frac{\exp(Q(s,k))}{\tau}} \quad (6)$$

Traditionally, the Boltzmann parameter τ should be decreasing over the time steps, such that the probabilities of high-interest actions will rise, whereas low-interest actions will converge towards a probability of 0. This mechanism ensures the convergence of the agents’ policy towards the optimal one, by reducing exploration in later steps, in favour of exploitation. However, and as we have already mentioned, we chose to disable the convergence mechanisms in our algorithms, because it prevents, by principle, continuous learning and adaptation.

We draw an action identifier j from the list of possible actions, according to Boltzmann probabilities (line 11). From this discrete identifier, we get the action’s parameters from the Action-SOM, which is tasked with learning the action space. We retrieve the neuron with identifier j , and take its prototype vector as the proposed action’s parameters (line 12).

We can note that this is somewhat symmetrical to what is done with the State-SOM. To learn the State-SOM, we use the data points, i.e., the observations, that come from the environment; to obtain a discrete identifier, we take the neurone with the closest prototype. For the Action-SOM, we start with a discrete identifier, and we take the prototype of the neuron with this identifier. However, we need to learn what are those prototype vectors. We do not have data points as for the State-SOM, since we do not know what is the “correct” action in each situation. In order to learn better actions, we apply an exploration step after choosing an action: the action’s parameters are perturbed by a random noise (lines 13-16).

In the original work of Smith (2002a), the noise was taken from a uniform distribution $\mathcal{U}_{[-\epsilon, +\epsilon]}$, which we will call the *epsilon* method in our experiments. However, in our algorithms, we implemented a normal, or *gaussian*, random distribution $\mathcal{N}(\mu, \sigma^2)$, where μ is the mean, which we set to 0 so that the distribution ranges over both negative and positive values, σ^2 is the variance, and σ is the standard deviation. ϵ and σ^2 are the “noise control parameter” for their respective distribution. The advantage over the uniform distribution is to have a higher probability of a small noise, thus exploring very close actions, while still allowing for a few rare but longer “jumps” in the action space. These longer jumps may help to escape local extremas, but should be rare, so as to slowly converge towards optimal actions most of the time, without overshooting them. This was not permitted by the uniform distribution, as the probability is the same for each value in the range $[-\epsilon, +\epsilon]$.

The noised action’s parameters are considered as the chosen action by the decision process, and the agent executes this action in the environment (line 17).

3.3.2 The learning process

After all agents executed their action, and the environment simulated the new state, agents receive a reward signal which indicates to which degree their action was a “good one”. From this reward, agents should improve their behaviour so that their next choice will be better. The learning process that makes this possible is formally described in Algorithm 2, and we detail it below.

First, we compute the Action-(D)SOM and State-(D)SOM neighborhoods (lines 11-13 and 14-16). Then, we update the Action-(D)SOM. Remember that we do not have the ground-truth for actions: we do not know which parameters yield the best rewards. Moreover, we explored the action space by randomly noising the proposed action; it is possible that the perturbed action is actually worse than the learned one. In this case, we do not want to update the Action-(D)SOM, as this would worsen the agent’s performances. We thus determine whether the perturbed action is better than the proposed action by comparing the received reward with the memorized interest of the proposed action, using the following equation:

$$r + \gamma \max_{j'} Q(s', j') \stackrel{?}{>} Q(s, j) \quad (7)$$

If the perturbed action is deemed better than the proposed one, we update the Action-(D)SOM towards the perturbed action (lines 17-21). To do so, we assume that the Best Matching Unit (BMU), i.e., the center of the neighborhood, is the neuron that was selected at the decision step, j . We then apply the corresponding update equation, Equation 3 for a SOM, or Equation 4 for a DSOM, to move the neurons’ prototypes towards the perturbed action.

Secondly, we update the actions’ interests, i.e., the Q-Table (line 22). To do so, we rely on the traditional Bellman’s equation. However, Smith’s algorithm introduces a difference in this equation to increase the learning speed. Indeed, the State- and Action-(D)SOMs offer additional knowledge about the states and actions: as they are discrete identifiers mapping to continuous vectors in a latent space, we can define a notion of *similarity* between states (resp. actions) by

Algorithm 2 Learning algorithm**Data** \mathcal{U} the neurons in the State-(D)SOM

- 1: \mathbf{U}_u the vector associated to neuron u in the State-(D)SOM
- 2: \mathcal{W} the neurons in the Action-(D)SOM
- 3: \mathbf{W}_w the vector associated to neuron w in the Action-(D)SOM
- 4: $P_U(u)$ is the position of neuron u in the State-(D)SOM grid
- 5: $P_W(w)$ is the position of neuron w in the Action-(D)SOM grid
- 6: $Q(s, a)$ the Q-value of action a in state s
- 7: η_U, η_W elasticity for State- and Action-(D)SOMs
- 8: $\alpha_Q, \alpha_U, \alpha_W$ learning rates for Q-Table, State-, Action-(D)SOMs
- 9: γ the discount factor
- 10: **function** LEARNING(Previous observations \mathbf{o} , New observations \mathbf{o}' , Received reward r , State hypothesis s , Chosen action identifier j , Chosen action parameters \mathbf{a})
- 11: **for** $u \in \mathcal{U}$ **do**
- 12: $\psi_U(u) \leftarrow \exp\left(-\frac{1}{\eta_U^2} \frac{\|P_U(u) - P_U(s)\|}{\|\mathbf{o} - \mathbf{U}_u\|}\right)$
- 13: **end for**
- 14: **for** $w \in \mathcal{W}$ **do**
- 15: $\psi_W(w) \leftarrow \exp\left(-\frac{1}{\eta_W^2} \frac{\|P_W(w) - P_W(j)\|}{\|\mathbf{a} - \mathbf{W}_w\|}\right)$
- 16: **end for**
- 17: **if** $r + \gamma \max_{j'} Q(s', j') \stackrel{?}{>} Q(s, j)$ **then**
- 18: **for** neuron $w \in \mathcal{W}$ **do**
- 19: $\mathbf{W}_w \leftarrow \alpha_W \|\mathbf{a} - \mathbf{W}_w\| \psi_W(w) (\mathbf{a} - \mathbf{W}_w) + \mathbf{W}_w$
- 20: **end for**
- 21: **end if**
- 22: $Q(s, j) \leftarrow \alpha_Q \psi_U(s) \psi_W(j) [r + \gamma \max_{j'} Q(i', j') - Q(s, j)] + Q(s, j)$
- 23: **for** neuron $u \in \mathcal{U}$ **do**
- 24: $\mathbf{U}_u \leftarrow \alpha_U \|\mathbf{o} - \mathbf{U}_u\| \psi_U(u) (\mathbf{o} - \mathbf{U}_u) + \mathbf{U}_u$
- 25: **end for**
- 26: **end function**

measuring the distance between the states' vectors (resp. actions' vectors). Similar states and actions will most likely have a similar interest, and thus each Q-Value is updated at each time step, instead of only the current state-action pair, by taking into account the neighborhoods of the State- and Action-(D)SOMs (computed on lines 11-13 and 14-16). Equation 8 shows the resulting formula:

$$Q_{t+1}(s, j) \leftarrow \alpha \psi_U(s) \psi_W(j) \left[r + \gamma \max_{j'} Q_t(s', j') \right] + (1 - \alpha) Q_t(s, j) \quad (8)$$

where s was the state hypothesis at step t , j was the chosen action identifier, r is the received reward, s' is the state hypothesis at step $t + 1$ (from the new observations). $\psi_U(s)$ and $\psi_W(j)$ represent, respectively, the neighborhood of the State- and Action-(D)SOMs, centered on the state s and the chosen action identifier j . Intuitively, the equation takes into account the interest of arriving in this new state, based on the maximum interest of actions available in the new state. This means that an action could yield a medium reward by itself, but still be very interesting because it allows to take actions with higher interests. On the contrary, an action with a high reward, but leading to a state with only catastrophic actions would have a low interest.

Finally, we learn the State-SOM, which is a very simple step (lines 23-25). Indeed, we have already mentioned that we know data points, i.e., observations, that have been sampled from the distribution of states by the environment. Therefore, we simply update the neurons' prototypes towards the received observation at the previous step. Prototype vectors are updated based on both their own distance to the data point, within the latent space, and the distance between their neuron and the best matching unit, within the 2D grid neighborhood (using the neighborhood computed on lines 11-13). This ensures that the State-SOM learns to represent states which appear in the environment.

Remark. In the presented algorithm, the neighborhood and update formulas correspond to a DSOM. When using the QSOM algorithm, these formulas must be replaced by their SOM equivalents. The general structure of the algorithm, i.e., the steps and the order in which they are taken, stays the same.

Remark. Compared to Smith’s algorithm, our extensions differ in the following aspects:

- DSOMs can be used in addition to SOMs.
- Hyperparameters are not annealed, i.e., they are constant throughout the simulation, so that agents can continuously learn instead of slowly converging.
- Actions are chosen through a Boltzmann distribution of probabilities based on their interests, instead of using the ϵ -greedy method.
- The random noise to explore the actions’ space is drawn from a Gaussian distribution instead of a uniform one.
- The neighborhood functions of the State- and Action-(D)SOMs is a gaussian instead of a linear one.
- The number of dimensions of the actions’ space in the following experiments is greater (6) than in Smith’s original experiments (2). This particularly prompted the need to explore other ways to randomly noise actions, e.g., the gaussian distribution. Note that some other methods have been tried, such as applying a noise on a single dimension each step, or randomly determining for each dimension whether it should be noised at each step; they are not disclosed in the results as they performed slightly below the gaussian method. Searching for better hyperparameters could yield better results for these methods.

4 Experiments and results

In order to validate our proposed algorithms, we ran some experiments on a Smart Grid use-case..

First, let us apply the algorithms and formal model on this specific use-case. The observation space, \mathbb{O} , is composed of the information that agents receive: the time (hour), the available energy, their personal battery storage, ... The full list of observations was defined in Section @ref(positioning-smartgrid-observations). These values range from 0 to 1, and we have 11 such values, thus we define $\mathbb{O}_l = [0, 1]^{11}$.

Similarly, actions are defined by multiple parameters: consume energy from grid, consume from battery, sell, ... These actions were presented in Section @ref(positioning-smartgrid-actions). To simplify the learning of actions, we constrain these parameters to the $[0, 1]$ range; they are scaled to the true agent’s action range outside the learning and decision processes. For example, let us imagine an agent with an action range of 6,000, and an action parameter, as outputted by the decision process, of 0.5, the scaled action parameter will be $0.5 \times 6,000 = 3,000$. We have 6 actions parameters, and thus define $\mathbb{A}_l = [0, 1]^6$.

In the sequel, we present the reward functions that we implemented to test our algorithms, as well as the experiments’ scenarii. Finally, we quickly describe the 2 algorithms that we chose as baselines: *DDPG* and *MADDPG*.

4.1 The Smart-Grid use-case

We use, to evaluate the QSOM and QDSOM algorithms, a Smart-Grid use case in which multiple producer-consumer (*prosumer*) agents learn to consume energy to satisfy their needs. The use-case is represented in Figure 4.

Learning agents receive *observations* $\in \mathbb{R}^{11}$ that describe the current state of the environment: they consist of *shared* observations $\in \mathbb{R}^8$ that are shared among all agents, such as the current hour or amount of available energy, and *local* observations $\in \mathbb{R}^3$ that are individual to each agent, and not accessible to others, such as the agent’s personal battery. Splitting between shared and local observations helps preserving the privacy of agents, by not sharing personal data. From these observations, agents must take *actions*, represented by vectors of parameters $\in \mathbb{R}^6$, which govern the amounts of energy to exchange: how much to consume from the smart grid, how much to buy, etc.

In practice, these observations and actions are interpolated to the $[0, 1]$ domain, so as to facilitate the learning algorithms, and especially the Self-Organizing Maps. Indeed, a dimension with a higher range than another would have a greater importance and would risk biasing the learning.

The simulated Smart Grid is connected to a national grid, which allows agents to buy and sell energy, although from more pollutant sources; it is also connected to an hydropower plant, which is considered to be local to the Smart Grid. This power plant generates the energy that is available to all agents at each time step of the simulation. Agents additionally produce a small quantity (e.g., from solar panels), which is kept in their personal battery. They may share this energy with other agents when necessary (e.g., to increase equity), consume it directly, or sell it to the national grid for some (monetary) profit.

Different *profiles* of prosumer agents are present in the grid, each representing a specific kind of building: a (small) Household, an (medium) Office, or a (large) School. Buildings’ profiles determine several characteristics, such as the *needs* that these buildings have, i.e., how much energy they would like to consume at each hour. These needs are taken from a public dataset of energy consumption in the United States (Ong and Clark 2014). Profiles also impact the range of action parameters: larger buildings may consume more energy than the smaller ones. In practice, the range was determined to be slightly higher than the maximum need over all hours, so that the buildings can decide to consume as

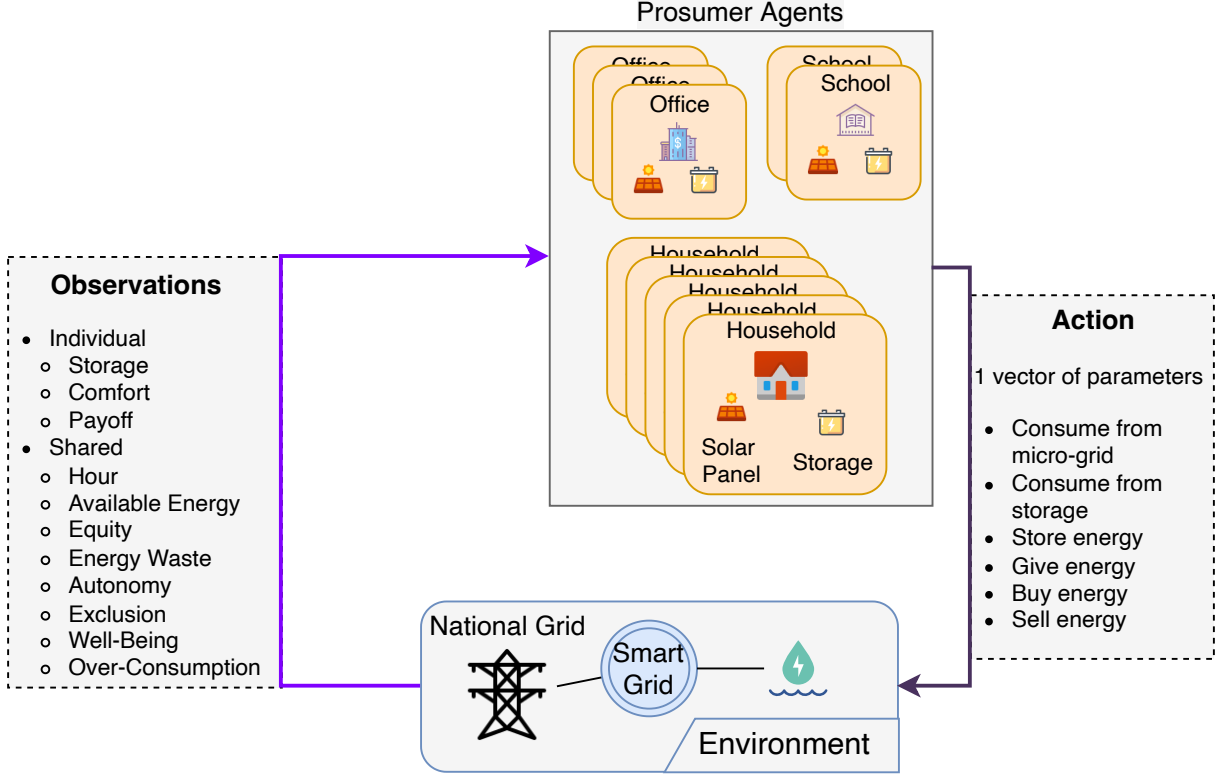


Figure 4: Illustration of the Smart Grid use-case. Multiple learning agents receive observations, and must decide to take actions, in order to exchange energy.

much as they need (yet, during the simulation, this might be a bad idea due to the environment’s state!). Similarly, the battery capacity depends on the profile, with larger buildings having access to higher capacities.

Agents make decisions based on the rewards they receive, which drive them towards the respect of one or several ethical considerations. The reward functions are described in the next section, and concern some considerations that are classical for smart grid: consuming energy to satisfy their needs and increase their comfort, ensuring the equity of comforts among agents, avoiding to over-consume.

4.2 Reward functions

We implemented multiple reward functions that each focus on different ethical stakes. Most of them are based on the principle of Difference Reward (Yliniemi and Tumer 2014) to facilitate the Credit Assignment. Additionally, two functions focus on multiple objectives, but with a rather naïve approach to scalarize, and another two focus on adaptation, i.e., the agents’ capacity to adapt their behaviour to changing mores, by making the reward function artificially change at a fixed point in time.

We give an intuitive definition and a mathematical formula for each of these reward functions below.

Equity Determine the agent’s contribution to the society’s equity, by comparing the current equity with the equity if the agent did not act. The agent’s goal is thus to maximize the society’s equity.

$$R_{eq}(agent) = (1 - Hoover(Comforts)) - (1 - Hoover(Comforts \setminus \{agent\}))$$

Over-Consumption Determine the agent’s contribution to over-consumption, by comparing the current over-consumed amount of energy, with the amount that would have been over-consumed if the agent did not act. The agent’s goal is thus to minimize society’s over-consumption.

$$R_{oc}(agent) = 1 - \frac{OC}{\sum_{\forall a} (Consumed_a + Stored_a)} - \frac{OC - (Consumed_{agent} + Stored_{agent})}{\sum_{\forall a \neq agent} (Consumed_a + Stored_a)}$$

Comfort Simply return the agent’s comfort, so that agents aim to maximize their comfort. This intuitively does not seem like an ethical stake, however it can be linked to Schwartz’ “hedonistic” value, and therefore is an ethical stake, focused on the individual aspect. We will mainly use this reward function in combination with others that focus on the societal aspect, to demonstrate the algorithms’ capacity to learn opposed moral values.

$$R_{comfort}(agent) = Comforts_{agent}$$

Multi-Objective Sum A first and simple reward function that combines multiple objectives, namely limitation of over-consumption and comfort. The goal of agents is thus to both minimize the society’s over-consumption while maximizing their own comfort. This may be a difficult task, because the simulation is designed so that there is a scarcity of energy most of the time, and agents will most likely over-consume if they all try to maximize their comfort. On the contrary, reducing the over-consumption means they need to diminish their comfort. There is thus a trade-off to be achieved between over-consumption and comfort.

$$R_{mos}(agent) = 0.8 \times R_{oc}(agent) + 0.2 \times R_{comfort}(agent)$$

Multi-Objective Product A second, but also simple, multi-objective reward functions. Instead of using a weighted sum, we multiply the reward together. This function is more punitive than the sum, as a low reward cannot be “compensated”. For example, let us consider a vector of reward components $[0.1, 0.9]$. Using the weighted sum, the result depends on the weights: if the first component has a low coefficient, then the result may actually be high. On contrary, the product will return $0.1 \times 0.9 = 0.09$, i.e., a very low reward. Any low component will penalize the final result.

$$R_{mop}(agent) = R_{oc}(agent) \times R_{comfort}(agent)$$

Adaptability1 A reward function that simulates a change in its definition after 2000 time steps, as if society’s ethical mores had changed. During the first 2000 steps, it behaves similarly as the Over-Consumption reward function, whereas for later steps it returns the mean of Over-Consumption and Equity rewards.

$$R_{ada1}(agent) = \begin{cases} R_{oc}(agent) & \text{if } t < 2000 \\ \frac{R_{oc}(agent) + R_{eq}(agent)}{2} & \text{else} \end{cases}$$

Adaptability2 Similar to Adaptability1, this function simulates a change in its definition. We increase the difficulty by making 2 changes, one after 2000 time steps, and another after 6000 time steps, and by considering a combination of 3 rewards after the second change.

$$R_{ada2}(agent) = \begin{cases} R_{oc}(agent) & \text{if } t < 2000 \\ \frac{R_{oc}(agent) + R_{eq}(agent)}{2} & \text{else if } t < 6000 \\ \frac{R_{oc}(agent) + R_{eq}(agent) + R_{comfort}(agent)}{3} & \text{else} \end{cases}$$

As we can see, the various reward functions have different aims. Some simple functions, such as *equity*, *overconsumption*, or *comfort*, serve as a baseline and building blocks for other functions. Nevertheless, they may be easy to optimize: for example, by consuming absolutely nothing, the *overconsumption* function can be satisfied. On the contrary, the *comfort* function can be satisfied by consuming the maximum amount of energy, such that the comfort is guaranteed to be close to 1. The two *multi-objective* functions thus try to force agents to learn several stakes at the same time, especially if they are contradictory, such as *overconsumption* and *comfort*. The agent thus cannot learn a “trivial” behaviour and must find the optimal behaviour that manages to satisfy both as much as possible. Finally, the *adaptability* functions go a step further and evaluate agents’ ability to adapt when the considerations change.

4.3 Scenarii

In order to improve the richness of our experiments, we designed several scenarii. These scenarii are defined by two variables: the agents’ consumption profile, and the environment’s size, i.e., number of agents.

The prosumer (learning) agents are instantiated with a profile, determining their battery capacity, their action range, and their needs, i.e., the quantity of energy they want to consume at each hour. These needs are extracted from real consumption profiles; we propose two different versions, the *daily* and the *annual* profiles. In the *daily* version, needs are averaged over every day of the year, thus yielding a need for each hour of a day: this is illustrated in Figure 5. This is a simplified version, averaging the seasonal differences; its advantages are a reduced size, thus decreasing the required computational resources, a simpler learning, and an easier visualization for humans. On the other hand, the *annual* version is more complete, contains seasonal differences, which improve the environment’s richness and force agents to adapt to important changes.

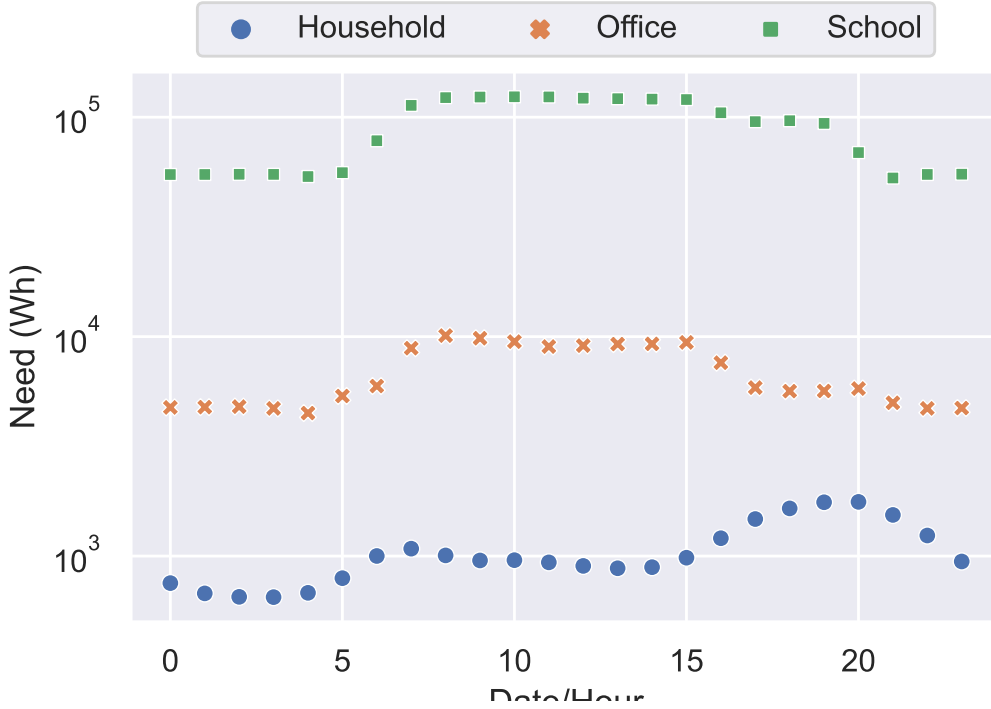


Figure 5: The agents’ needs for every hour of the day in the *daily* profile.

The second property is the environment size. We wanted to test our algorithms with different sets of agents, to ensure the scalability of the approach, in the sense that agents are able to learn a correct behaviour and adapt to many other agents in the same environment. This may be difficult as the number of agents increases, since there will most certainly be more conflicts. We propose a first, *small* environment, containing 20 Households agents, 5 Office agents, and 1 School agent. The second environment, *medium*, contains roughly 4 times more agents than in the *small* case: 80 Household agents, 19 Office agents, and 1 School.

4.3.1 DDPG and MADDPG baselines

In order to prove our algorithms’ advantages, we chose to compare them to the well-known DDPG (Lillicrap et al. 2015) and its multi-agent extension, MADDPG (Lowe et al. 2017).

DDPG (*Deep Deterministic Policy Gradient*) is one of the algorithms that extended the success of Deep Reinforcement Learning to continuous domains (Lillicrap et al. 2015). It follows the quite popular Actor-Critic architecture, which uses two different Neural Networks: one for the Actor, i.e., to decide which action to perform at each time step, and another for the Critic, i.e., to evaluate whether an action is interesting. We chose it as a baseline since it focuses on problems with similar characteristics, e.g., continuous domains, and is a popular baseline in the community.

MADDPG (*Multi-Agent Deep Deterministic Policy Gradient*), extends the idea of DDPG to the multi-agent setting (Lowe et al. 2017), by relying on the *Centralized Training - Decentralized Execution* idea. It is one of the most used methods to improve multi-agent learning, by sharing data among agents during the learning phase. This helps agents make a model of other agents and adapt to their respective behaviours. However, during execution, sharing data in the same manner is often impracticable or undesirable, as it would impair privacy and require some sort of communication between agents; thus, data is not shared any more at this point (Decentralized Execution). As such, Centralized Training - Decentralized Execution makes a distinction between training and execution, and is thus inadequate for continuous learning, and constant adaptation to changes. On the other hand, if we were to make agents continuously learn with centralized data sharing, even in the execution phase, we would impair privacy of users that are represented or impacted by the agents. These reasons are why we chose not to use this setting for our own algorithms QSOM and QDSOM. While we do not use centralized training, we want to compare them to an algorithm that uses it, such as MADDPG, in order to determine whether there would be a performance gain, and what would be the trade-off between performance and privacy. In MADDPG, the Centralized Training is simply done by using a centralized Critic network, which receives observations, actions, and rewards from all agents, and evaluates all agents’ actions. The Actor networks, however, are still individualized: each agent has its own network, which the other agents cannot access. During the training phase,

the Critic network is updated thanks to the globally shared data, whereas Actor networks are updated through local data and the global Critic. Once the learning is done, the networks are frozen: the Critic does not require receiving global data any more, and the Actors do not rely on the Critic any more. Only the decision part, i.e., which action should we do, is kept, by using the trained Actor network as-is.

4.4 Results

Several sets of experiments were performed:

- First, numerous experiments were launched to search for the best hyperparameters of each algorithm, to ensure a fair comparison later. Each set of hyperparameters was run 10 times to obtain average results, and a better statistical significance. In order to limit the number of runs and thus the computational resources required, we decided to focus on the *adaptability2* reward for these experiments. This function is difficult enough so that the algorithms will not reach almost 100% immediately, which would make the hyperparameter search quite useless, and is one of the 2 that interest us the most, along with *adaptability1*, so it makes sense that our algorithms are optimized for this one. The *annual* consumption profile was used to increase the richness, but the environment size, i.e., number of agents, was set to *small* in order to once again reduce the computational power and time.
- Then, the 4 algorithms, configured with their best hyperparameters, were compared on multiple settings: both *annual* and *daily* consumption profiles, both *small* and *medium* sizes of environment, and all the reward functions. This resulted in $2 \times 2 \times 7$ scenarii, which we ran 10 times for each of the 4 algorithms.

In the following results, we define a run’s *score* as the average of the global rewards per step. The global reward corresponds to the reward, without focusing on a specific agent. For example, the *equity* reward compares the Hoover index of the whole environment to a hypothetical environment without the agent. The global reward, in this case, is simply the Hoover index of the entire environment. This represents, intuitively, how the society of agents performed, globally. Taking the average is one of the simplest methods to get a single score for a given run, which allows comparing runs easily.

4.4.1 Searching for hyperparameters

Table 1, Table 2, Table 3, and Table 4 summarize the best hyperparameters that have been found for each algorithm, based on the average runs’ score obtained when using these parameters.

Table 1: Best hyperparameters on 10 runs for the *QSOM* algorithm, using the *annual small* scenario and *adaptability2* reward function.

Parameter	Value	Description
State-SOM shape	12x12	Shape of the neurons’ grid
State-SOM learning rate	0.5	Update speed of State-SOM neurons
Action-SOM shape	3x3	Shape of the neurons’ grid
Action-SOM learning rate	0.2	Update speed of Action-SOM neurons
Q Learning rate	0.6	Update speed of Q-Values
Discount rate	0.9	Controls the horizon of rewards
Action perturbation	gaussian	Method to randomly explore actions
Action noise	0.06	Parameter for the random noise distribution
Boltzmann temperature	0.4	Controls the exploration-exploitation

Table 2: Best hyperparameters on 10 runs for the *QDSOM* algorithm, using the *annual small* scenario and *adaptability2* reward function.

Parameter	Value	Description
State-DSOM shape	12x12	Shape of the neurons' grid
State-DSOM learning rate	0.8	Update speed of State-DSOM neurons
State-DSOM elasticity	1	Coupling between State-DSOM neurons
Action-DSOM shape	3x3	Shape of the neurons' grid
Action-DSOM learning rate	0.7	Update speed of Action-DSOM neurons
Action-DSOM elasticity	1	Coupling between Action-DSOM neurons
Q Learning rate	0.8	Update speed of Q-Values
Discount rate	0.95	Controls the horizon of rewards
Action perturbation	gaussian	Method to randomly explore actions
Action noise	0.09	Parameter for the random noise distribution
Boltzmann temperature	0.6	Controls the exploration-exploitation

Table 3: Best hyperparameters on 10 runs for the *DDPG* algorithm, using the *annual small* scenario and *adaptability2* reward function.

Parameter	Value	Description
Batch size	256	Number of samples to use for training at each step
Learning rate	5e-04	Update speed of neural networks
Discount rate	0.99	Controls the horizon of rewards
Tau	5e-04	Target network update rate
Action perturbation	gaussian	Method to randomly explore actions
Action noise	0.11	Parameter for the random noise distribution

Table 4: Best hyperparameters on 10 runs for the *MADDPG* algorithm, using the *annual small* scenario and *adaptability2* reward function.

Parameter	Value	Description
Batch size	128	Number of samples to use for training at each step
Buffer size	50000	Size of the replay memory.
Actor learning rate	0.01	Update speed of the Actor network
Critic learning rate	0.001	Update speed of the Critic network
Discount rate	0.95	Controls the horizon of rewards
Tau	0.001	Target network update rate
Noise	0.02	Controls a gaussian noise to explore actions
Epsilon	0.05	Controls the exploration-exploitation

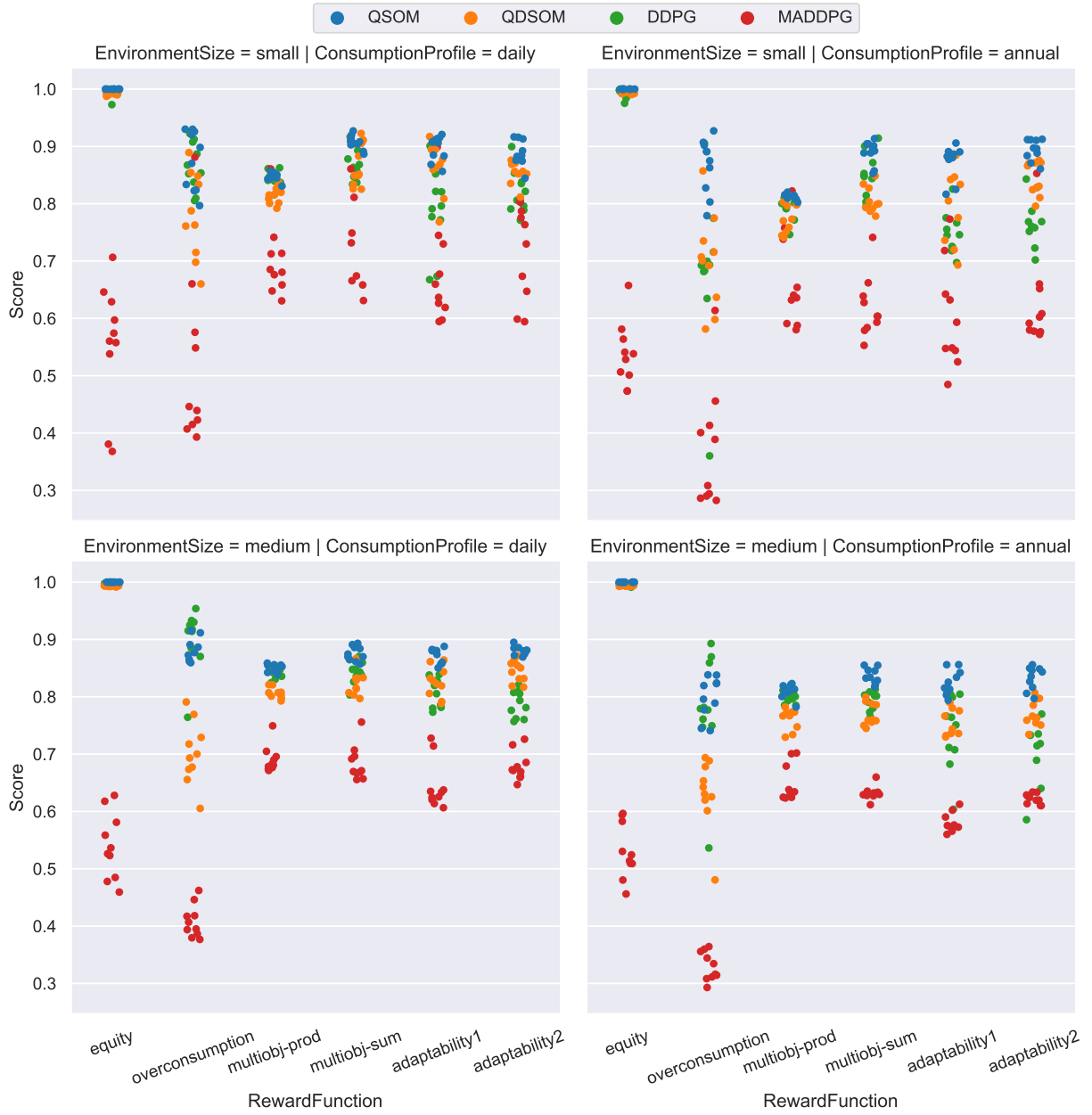


Figure 6: Distribution of scores per learning algorithm, on every scenario, for 10 runs with each reward function.

4.4.2 Comparing algorithms

Table 5: Average score for 10 runs of each algorithm, on each reward function and each scenario. The standard deviation is shown inside parentheses.

RewardFunction	QSOM	QDSOM	DDPG	MADDPG
Scenario: daily / small				
equity	1.00 (+/- 0.00)	0.99 (+/- 0.00)	0.99 (+/- 0.01)	0.56 (+/- 0.11)
overconsumption	0.88 (+/- 0.05)	0.78 (+/- 0.08)	0.87 (+/- 0.04)	0.52 (+/- 0.15)
multiobj-sum	0.91 (+/- 0.01)	0.87 (+/- 0.04)	0.87 (+/- 0.03)	0.76 (+/- 0.11)
multiobj-prod	0.85 (+/- 0.01)	0.82 (+/- 0.02)	0.84 (+/- 0.01)	0.70 (+/- 0.07)
adaptability1	0.90 (+/- 0.02)	0.87 (+/- 0.05)	0.79 (+/- 0.07)	0.68 (+/- 0.09)
adaptability2	0.89 (+/- 0.02)	0.86 (+/- 0.02)	0.82 (+/- 0.04)	0.72 (+/- 0.08)
Scenario: daily / medium				
equity	1.00 (+/- 0.00)	0.99 (+/- 0.00)	1.00 (+/- 0.00)	0.54 (+/- 0.06)
overconsumption	0.89 (+/- 0.02)	0.70 (+/- 0.05)	0.90 (+/- 0.05)	0.41 (+/- 0.03)
multiobj-sum	0.88 (+/- 0.01)	0.82 (+/- 0.02)	0.84 (+/- 0.02)	0.68 (+/- 0.03)
multiobj-prod	0.85 (+/- 0.01)	0.81 (+/- 0.01)	0.84 (+/- 0.01)	0.69 (+/- 0.02)
adaptability1	0.87 (+/- 0.01)	0.83 (+/- 0.03)	0.81 (+/- 0.03)	0.64 (+/- 0.04)
adaptability2	0.88 (+/- 0.01)	0.84 (+/- 0.02)	0.79 (+/- 0.02)	0.68 (+/- 0.02)
Scenario: annual / small				
equity	1.00 (+/- 0.00)	0.99 (+/- 0.00)	0.99 (+/- 0.01)	0.54 (+/- 0.06)
overconsumption	0.87 (+/- 0.05)	0.70 (+/- 0.08)	0.68 (+/- 0.14)	0.37 (+/- 0.11)
multiobj-sum	0.89 (+/- 0.02)	0.81 (+/- 0.02)	0.85 (+/- 0.04)	0.62 (+/- 0.05)
multiobj-prod	0.81 (+/- 0.00)	0.78 (+/- 0.03)	0.79 (+/- 0.02)	0.66 (+/- 0.08)
adaptability1	0.87 (+/- 0.03)	0.80 (+/- 0.07)	0.75 (+/- 0.04)	0.60 (+/- 0.09)
adaptability2	0.89 (+/- 0.02)	0.84 (+/- 0.03)	0.77 (+/- 0.04)	0.63 (+/- 0.09)
Scenario: annual / medium				
equity	1.00 (+/- 0.00)	0.99 (+/- 0.00)	1.00 (+/- 0.00)	0.53 (+/- 0.05)
overconsumption	0.80 (+/- 0.04)	0.63 (+/- 0.06)	0.78 (+/- 0.10)	0.33 (+/- 0.02)
multiobj-sum	0.84 (+/- 0.01)	0.77 (+/- 0.02)	0.79 (+/- 0.02)	0.63 (+/- 0.01)
multiobj-prod	0.81 (+/- 0.01)	0.76 (+/- 0.02)	0.80 (+/- 0.01)	0.65 (+/- 0.03)
adaptability1	0.82 (+/- 0.02)	0.76 (+/- 0.02)	0.74 (+/- 0.06)	0.58 (+/- 0.02)
adaptability2	0.83 (+/- 0.02)	0.77 (+/- 0.02)	0.71 (+/- 0.06)	0.62 (+/- 0.01)

The results presented in Figure 6 and Table 5 show that the QSOM algorithm performs better. We use the Wilcoxon statistical test, which is the non-parametric equivalent of the well-known T-test, to determine whether there is a statistically significant difference in the means of runs' scores between different algorithms. Wilcoxon's test, when used with the *greater* alternative, assumes a null hypothesis that the 2 algorithms have similar means, or that the observed difference is negligible and only due to chance. The Wilcoxon method returns the *p-value*, i.e, the likelihood of the null hypothesis being true. When $p < \alpha = 0.05$, we say that it is more likely that the null hypothesis can be refuted, and we assume that the alternative hypothesis is the correct one. The alternative hypothesis, in this case, is that

the QSOM algorithm obtains better results than its opposing algorithm. We thus compare algorithms 2-by-2, on each reward function and scenario.

The statistics, presented in Table Table 6, prove that the QSOM algorithm statistically outperforms other algorithms, in particular DDPG and MADDPG, on most scenarii and reward functions, except a few cases, indicated by the absence of * next to the *p-value*. For example, DDPG obtains similar scores on the *daily / small overconsumption* and *multiobj-prod* cases, as well as *daily / medium overconsumption*, and *annual / medium overconsumption*. QDSOM is also quite on par with QSOM on the *daily / small adaptability1* case. Yet, MADDPG is consistently outperformed by QSOM.

Table 6: Comparison of the *QSOM* algorithm with the others, using a Wilcoxon statistical test, with the ‘greater’ alternative.

RewardFunction	Wilcoxon’s p-value (QSOM vs ...)		
	QDSOM	DDPG	MADDPG
Scenario: daily / small			
equity	5.41e-06***	5.41e-06***	5.41e-06***
overconsumption	0.005748 **	0.289371	0.000103***
multiobj-sum	0.011615 *	0.001045 **	0.000525***
multiobj-prod	0.000162***	0.071570	0.000752***
adaptability1	0.061503	6.50e-05***	6.50e-05***
adaptability2	0.001440 **	0.000363***	5.41e-06***
Scenario: daily / medium			
equity	5.41e-06***	5.41e-06***	5.41e-06***
overconsumption	5.41e-06***	0.973787	5.41e-06***
multiobj-sum	3.79e-05***	0.000162***	5.41e-06***
multiobj-prod	5.41e-06***	0.005748 **	5.41e-06***
adaptability1	0.000363***	5.41e-06***	5.41e-06***
adaptability2	1.08e-05***	5.41e-06***	5.41e-06***
Scenario: annual / small			
equity	5.41e-06***	5.41e-06***	5.41e-06***
overconsumption	3.79e-05***	0.000363***	5.41e-06***
multiobj-sum	5.41e-06***	0.009272 **	5.41e-06***
multiobj-prod	0.000363***	0.000525***	0.000752***
adaptability1	0.007345 **	2.17e-05***	5.41e-06***
adaptability2	0.000363***	5.41e-06***	5.41e-06***
Scenario: annual / medium			
equity	5.41e-06***	5.41e-06***	5.41e-06***
overconsumption	5.41e-06***	0.342105	5.41e-06***
multiobj-sum	5.41e-06***	5.41e-06***	5.41e-06***
multiobj-prod	5.41e-06***	0.009272 **	5.41e-06***
adaptability1	5.41e-06***	0.000103***	5.41e-06***
adaptability2	3.79e-05***	5.41e-06***	5.41e-06***

Signif. codes: 0 <= ‘***’ < 0.001 < ‘**’ < 0.01 < ‘*’ < 0.05

Table 7: Comparison of the *QDSOM* algorithm with the others, using a Wilcoxon statistical test, with the ‘greater’ alternative.

RewardFunction	Wilcoxon’s p-value (QDSOM vs ...)		
	QSOM	DDPG	MADDPG
Scenario: daily / small			
equity	1.000	0.999475	5.41e-06***
overconsumption	0.996	0.995535	0.000752***
multiobj-sum	0.991	0.684736	0.014403 *
multiobj-prod	1.000	0.998560	0.000752***
adaptability1	0.947	0.007345 **	0.000363***
adaptability2	0.999	0.007345 **	5.41e-06***
Scenario: daily / medium			
equity	1.000	0.999935	5.41e-06***
overconsumption	1.000	0.999989	5.41e-06***
multiobj-sum	1.000	0.982269	5.41e-06***
multiobj-prod	1.000	1.000000	5.41e-06***
adaptability1	1.000	0.082747	5.41e-06***
adaptability2	1.000	2.17e-05***	5.41e-06***
Scenario: annual / small			
equity	1.000	0.990728	5.41e-06***
overconsumption	1.000	0.369682	2.17e-05***
multiobj-sum	1.000	0.997402	5.41e-06***
multiobj-prod	1.000	0.938497	0.001943 **
adaptability1	0.994	0.037628 *	6.50e-05***
adaptability2	1.000	0.000363***	0.000103***
Scenario: annual / medium			
equity	1.000	0.999475	5.41e-06***
overconsumption	1.000	0.999637	5.41e-06***
multiobj-sum	1.000	0.992655	5.41e-06***
multiobj-prod	1.000	1.000000	5.41e-06***
adaptability1	1.000	0.369682	5.41e-06***
adaptability2	1.000	0.001440 **	5.41e-06***

Signif. codes: 0 <= '***' < 0.001 < '**' < 0.01 < '*' < 0.05

Figure 7 shows the evolution of individual rewards received by agents over the time steps, in the *annual / small* scenario, using the *adaptability2* reward function. We chose to focus on this combination of scenario and reward function as they are, arguably, the most interesting. *Daily* scenarios are perhaps too easy for the agents as they do not include as many variations as the *annual*; additionally, *small* scenarios are easier to visualize and explore, as they contain fewer agents than *medium* scenarios. Finally, the *adaptability2* is retained for the same arguments that made us choose it for the

hyperparameters search. We show a moving average of the rewards in order to erase the small and local variations to highlight the larger trend of the rewards’ evolution.

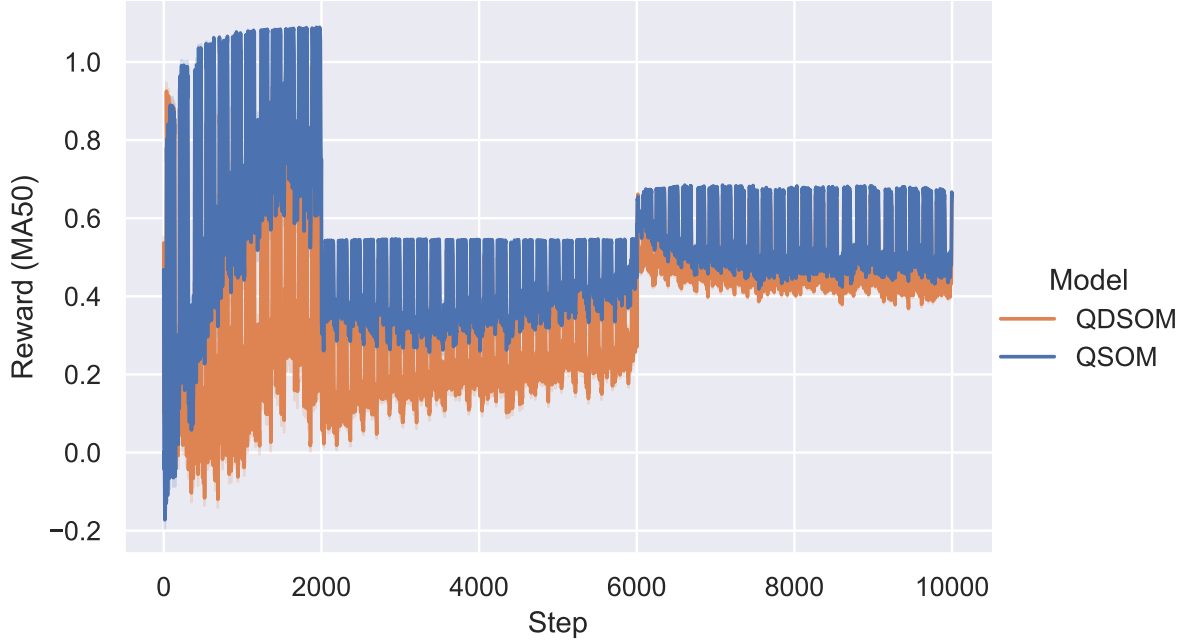


Figure 7: Agents Rewards

We can see from the results that the *small* scenarii seem to yield a slightly better score than the *medium* scenarii. Thus, agents are impacted by the increased number of other agents, and have difficulties learning the whole environment dynamics. Still, the results reported for the *medium* scenarii are near the *small* results, and very close to 1. Even though there is indeed an effect of the environment size on the score, this hints towards the scalability of our approach, as the agents managed to learn a “good” behaviour that yields high rewards.

5 Discussion

In this article, we presented two new reinforcement learning algorithms, QSOM and QDSOM.

We recall that the principal important aspects and limitations identified in the State of the Art were the following:

- Using continuous and multi-dimensional domains to improve the environment’s richness.
- Continuously learning and adapting to changes in the environment, including in the reward function, i.e., the structure that encodes and captures the ethical considerations that agents should learn to exhibit.
- Learning in a multi-agent setting, by taking into account the difficulties posed by the presence of other agents.

The continuous and multi-dimensional aspect was solved by design, thanks to the SOMs and DSOMs that we use in our algorithms. They learn to handle the complex observations and actions domains, while advantageously offering a discrete representation that can be leveraged with the Q-Table, permitting a modular approach. This modular approach, and the use of Q-Tables, allow for example to compare different actions, which is not always possible in end-to-end Deep Neural Networks.

The continuous adaptation was also handled by our design choices, notably by disabling traditional convergence mechanisms. The use of (D)SOMs also help, as the representation may shift over time by moving the neurons. Additionally, our experiments highlight the ability of our algorithms to adapt, especially when compared to other algorithms, through the specific *adaptability1* and *adaptability2* functions.

Finally, challenges raised by the multi-agent aspect were partially answered by the use of Difference Rewards to create the reward functions. On the other hand, the agents themselves have no specific mechanism that help them learn a behaviour while taking account of the other agents in the shared environment, e.g., contrary to Centralized Training

algorithms such as MADDPG. Nevertheless, our algorithms managed to perform better than MADDPG on the proposed scenarios and reward functions, which means that this limitation is not crippling.

Our algorithms still suffer from a few limitations that we highlight here.

- As we already mentioned, the multi-agent aspect could be improved, for example by adding communication mechanisms between agents. Indeed, by being able to communicate, agents could coordinate their actions so that the joint-action could be even better. Let us assume that an agent, which approximately learned the environment dynamics, believes that there is not much consumption at 3AM, and chooses the strategy of replenishing its battery at this moment, so as to have a minimal impact on the grid. Another agent may, at some point, face an urgent situation that requires it to consume exceptionally at 3AM this day. Without coordination, the 2 agents will both consume an important amount of energy at the same time, thus impacting the grid and potentially over-consuming. On the other hand, if the agents could communicate, the second one may inform other agents of its urgency. The first one would perhaps choose to consume only at 4AM, or they would both negotiate an amount of energy to share, in the end proposing a better joint-action than the uncoordinated sum of their individual actions. However, such communication should be carefully designed in a privacy-respectful manner.
- The algorithms have not been tested on other (baseline) environments. This limits their results and promises: it might happen that their success, compared to DDPG and MADDPG especially, is due to some specificities of the Smart Grid environment. In particular, recent Deep Reinforcement Learning algorithms target use-cases with huge state-action spaces, e.g., taking input directly from the screen (pixels), or emitting physical actions concerning dozens of joints. Although our use-case used more dimensions (11 for states and 6 for actions) than Smith's original experiments, it does not compare to such environments. The performance of QSOM and QDSOM on them thus remains uncertain.

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