Towards a Self-Organization Mechanism for Agent Associations in Electricity Spot Markets

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Abstract: In the course of the last years, the liberalization of electricity markets induced the creation of power exchanges which allow participants to the trade electricity-related products in a competitive manner. Yet, in today's market structures small-scale entities like photovoltaic plants or households are prevented from direct participation because of capacity-related barriers to entry. To address this problem, the following paper introduces a mechanism for self-organizing agents which allows actors to join forces by aggregating their generation and consumption capacities. More specifically, we consider a market setting where participants trade active power products by forming product-related associations in a decentralized, temporally flexible fashion. Taking topology-related aspects of the grid into account, the approach accounts for the current trend towards more location-aware, regional-oriented market structures and thus provides the potential for a more efficient power provision.

1 Introduction

In recent years, several driving forces gave impetus to both an organizational and technical restructuring of the electricity domain which is mainly characterized by two trends. First, energy regulations which were enacted in many countries worldwide induced a liberalization of electricity markets entailing the creation of power exchanges where actors can trade electricity-related products in a competitive manner. Second, depleting fossil sources and a growing environmental awareness gave rise to an increased integration of distributed energy resources (DER) like photovoltaic (PV), combined heat and power (CHP) or wind energy plants (WEP) into the public power grid. In contrast to conventional fossil-based types, these kinds of units typically provide smaller generation potentials in the range from some kW to a few MW with a fluctuating and limited or even non-controllable feed-in.

However, though interrelated, in today's market structures both trends are commonly not sufficiently aligned from a conceptual point of view: first, power exchanges typically prescribe minimum capacity thresholds which have to be fulfilled by actors in order to be allowed to join the market. As a consequence, small-scale entities – both on generation and consumption side – are prevented from direct participation because of insufficient potentials. Even in bilateral markets similar problems arise when actors face bids exceeding their individual capabilities. Second, power production from renewable sources is subsidized by regulation in many countries worldwide to stimulate the construction of distributed energy resources. If these guaranteed payments expire in the future, according plants face an increased pressure to cover their generation costs under competitive market conditions. Third, non-controllable generation and consumption units are generally exposed to stochastic effects and are thus not able to guarantee an exact fulfillment of concluded trades. Short-term deviations from contractually specified amounts of electricity have to be compensated by transmission system operators in real time using expensive control energy.

In order to tackle these problems, the concept of a virtual power plant (VPP) has been conceived in the course of the last years. In its most common sense, a VPP aggregates a set of electrical producers, consumers or storage into a single entity in order to pursue a joint goal. In the context of electricity markets (both bilateral and mediated), a VPP can enable small-scale actors to trade products which otherwise would have exceeded their individual generation or consumption potentials by cumulating capacities [FEN09]. This way, participants additionally gain increased market power and are thus able to compete in the market more successfully. Finally, stochastic effects can be compensated by pooling actors with complementing capabilities (e.g. producers and storage), thus allowing a more reliant supply of traded products.

However, while this intention of a VPP is commonly understood, the way how participants are internally organized and controlled can be very varying. Most approaches proposed to date typically assume a fixed (i.e. temporally not changing) set of participants which are supervised by a central control logic where coordination is primarily done with regard to economical aspects (see Section 2). However, considering the domain of electricity markets (and particularly spot markets) where actors form VPPs to overcome the above mentioned problems, present concepts exhibit several drawbacks with regard to the following aspects:

- *Temporal Flexibility*. Assuming a temporally fixed set of VPP participants which are not able to flexibly reorganize over time prohibits actors to respond to short-term market conditions and price fluctuations. Moreover, considering the steady increase in the number of DER as well as current trends in the e-mobility domain and the accompanying integration of electric vehicles into the public grid, the amount of actors with stochastic behavior is expected to further grow in the upcoming years. Since trading activities of such actors are commonly based on prognosticated production and consumption values, VPPs composed of a temporally fixed and disadvantageous combination of stochastic participants can be unfavorably exposed to unpredictable changes in environmental and behavioral conditions, respectively, which potentially entails economical inefficiencies for participants.

- *Autonomy*. Assuming self-interested behavior of market participants, a centralized organization of VPP members which are supervised by a single control unit often contradicts the common intention of each participant to maximize its own profits. Being bound to a superior entity prohibits actors to flexibly apply their own trading strategies and preserve autonomy with regard to market activities.

- *Topology Awareness*. To our knowledge, there are no present trading-related VPP approaches which take topological aspects of the grid into account. However, particularly with regard to future market settings which are expected to increasingly integrate regional aspects [BBRA10, RHS09], considering the location of VPP participants in the network becomes more and more important. For instance, taking topological aspects into account allows VPPs to provide ancillary services or prevent congestions by restricting membership to specific grid districts.

Against this background, the following work introduces a method for the flexible formation of VPPs in both today's and future electricity markets. More precisely, we provide a conceptual solution for the above mentioned drawbacks by proposing an approach where participants *autonomously* organize themselves into VPPs in a dynamic, *temporally flexible* fashion, being *topology aware* by taking location-related aspects into account. With regard to the considered market setting, the work is restricted to *spot markets* where *active power products* are traded in temporally iterative cycles. Because the proposed approach strives for an agent-based design and VPPs exclusively consisting of consumers can be a reasonable actor in electricity markets as well [LS10], we simply speak of *associations* and refer to their participants as *agents*.

The remainder of this paper is structured as follows. Chapter 2 describes work which is related to the given problem domain. Chapter 3 gives an overview on different market types and derives an abstract setting which is independent from specific market designs and used in the context of our work. Chapter 4 introduces the self-organization mechanism for the formation of agent associations in electricity spot markets. Chapter 5 concludes the paper and describes future work to be addressed.

2 Related Work

The following section provides an overview on the most important work with regard to the above described problem of forming associations of individual actors in order to achieve a joint surplus. More precisely, we discuss concepts from the domains of electrical power supply as well as game theory and distributed artificial intelligence (DAI).

2.1 Electrical Power Supply

Virtual power plants were and still are topic of research in several R&D projects conducted in the domains of electrical power supply and energy management.

In the context of the 2006 completed European initiative *Distributed Generation with High Penetration of Renewable Energy Sources* (DISPOWER) a Power Flow and Power Quality Management System was developed which essentially represents a VPP infrastructure integrating a static pool of controllable consumption, storage and power quality devices on the low-voltage level [DSS06]. Participants are technically connected by means of interface boxes and supervised by a central control unit. Major goals of the project were an optimization of device operation and enabling of power quality control.

The 2009 completed R&D initiative *Flexible Electricity Networks to Integrate the expected Energy Evolution* (FENIX) [FEN09] considered the idea of a virtual power plant from two different perspectives: First, the concept of commercial virtual power plants (CVPPs) was conceived which aggregate an arbitrary set of DER to allow a participation in electricity markets maximizing the members' economical benefit. With regard to product provision, in CVPPs the geographical location of units is generally not considered. In case a market is restricted to a specific area, the corresponding portfolio of DER is simply restricted to this area as well. As second type, the concept of technical virtual power plants (TVPPs) was developed to provide local system management services for distribution system operators as well as ancillary services for transmission system operators. Contrary to the case of a CVPP, the products offered by a TVPP are bounded to specific districts in the grid, thus requiring participating units to be located in appropriate geographic areas. To demonstrate both VPP concepts, two demonstrations were conducted in the field where in both cases a central control logic was applied.

Further VPP-related investigations are currently carried out under the banner of the German joint research initiative E-Energy [E-E11]: In the context of the *eTelligence* project, VPPs are considered as a market player of a regional electricity market where trading is restricted to a geographically constrained grid district. Besides a practical demonstration in the field, the market and its participants are conceptually examined in the context of an IT-related reference architecture where players are integrated by means of market agents representing the trading interface to the market [BBRA10]. With regard to the VPP design, participants are supervised by a central control unit.

As another E-Energy initiative, the project *RegModHarz* strives for a practical VPP implementation integrating a high amount of producers, controllable consumers and storage located in the German district Harz [RHS09]. Underlying intention is the provision of electricity products and ancillary services which are to be traded on a dedicated electronic market platform. Again, the pool of VPP members is supervised in a centralized fashion.

2.2 Game Theory and Distributed Artificial Intelligence

Theoretical concepts for the formation of actor associations have been studied in the domain of game theory – more specifically in one of its branches termed cooperative game theory – for years. In contrast to non-cooperative game theory, which considers the individual agent as basic model element, cooperative game theory examines how groups of agents (coalitions) can effectively form and how the generated surplus can be distributed among participants guaranteeing criteria like stability or fairness.

The problem of coalition formation (CF) is formalized as a *characteristic function game* (or *coalitional game*) $G = \langle A, v \rangle$ where A is a set of agents and $v : 2^A \rightarrow \mathbb{R}$ is referred to as the *characteristic function* of the game assigning a real-valued *payoff* $v(C)$ to each coalition $C \subseteq A$.[1] Now, cooperative game theory provides different *solution concepts* for coalitional games addressing the two essential questions of which coalitions to form and how to divide the gained payoff among members, where both of these issues can generally depend on each other (for instance, agents may want to join coalitions which provide

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[1] With regard to our context it has to be noted that cooperative game theory is totally silent about the origin of the characteristic function and assumes it generally to be given.

the highest benefit). Well-known examples for solution concepts include the *core*, representing the set of all surplus distributions guaranteeing *stable* coalitions (in the sense that no subset of agents has the incentive to leave because of a higher payoff), or the *Shapley value*, allowing a *fair* distribution by specifying the payoff based on the average marginal contribution an agent makes to a coalition.

Although appealing because of their mathematical justification, most game theoretical results are associated with several disadvantages when it comes to their practical application, particularly when considering IT-related, distributed systems. Here, two major problems arise: First, many concepts are associated with combinatorial, NP-hard calculations which become intractable when coping with a larger set of agents. Second, most solutions are not suitable to be calculated in a decentralized, parallel fashion, which contradicts the general paradigm of distributed systems.

Thus, in the course of the last years several approaches have been proposed in the field of distributed artificial intelligence which consider coalition formation particularly constrained by the requirement of practical applicability, often adjusting game theoretical concepts to reduce complexity. In this domain, the problem of forming coalitions is often considered as a three phase process comprising the steps of (1) coalition structure generation, (2) solving the optimization problem under consideration, and (3) distributing the resulting payoff [SLA$^+$99]. Particularly the first problem, coalition structure generation (CSG), has gained much attention in the course of the last years. Based on the notion of characteristic function games, general goal of CSG is the partitioning of the set of agents into mutually disjoint coalitions such that social welfare is maximized. Being a NP-hard optimization problem, several methods have been proposed to reduce computational complexity which can be generally classified into dynamic programming (DP), anytime and heuristical algorithms [RJ08]. General idea of DP approaches is to recursively divide the optimization problem into subtasks to avoid redundant computations. Prominent candidates offering such capabilities were proposed by Rothkopf et al. [RPH95] and Rahwan and Jennings [RJ08]. While DP approaches generally provide the lowest worst case complexity with regard to an optimal solution, they do not provide anytime capabilities which is particularly disadvantageous when coping with larger sets of agents. According anytime algorithms generally start with a first solution which is guaranteed to be in a bound from optimal and steadily improve on it until the optimum is found or another termination condition ist met. Corresponding approaches were proposed by Sandholm et al. [SLA$^+$99], Dang and Jennings [DJ04] or Rahwan et al. [RRJG09]. Particularly, Michalak et al. recently proposed an anytime algorithm for solving the CSG problem in a decentralized manner [MSR$^+$10]. Finally, a number of heuristical methods have been proposed to reduce computational costs. For instance, Shehory and Kraus [SK98] put constraints on the size of coalitions to reduce complexity, while Sen and Dutta [SD00] apply an order-based genetic algorithm to search for (near-)optimal partitions. Heuristical approaches do not make any guarantees regarding the quality of their solutions but generally scale up well with the number of agents.

3 Market Setting

Generally the self-organization mechanism introduced in this paper aims to be as universal as possible with regard to its application to different market scenarios. Thus, the following section derives a setting which categorizes participants into different market roles and abstracts from specific market models by determining general trading-related use cases which are common for all present and future types of electricity markets.
We start by analyzing the different contributions which agents can make to an association and the active power product it intends to provide, respectively. Clearly, the capability of an actor and thus its role in the market depends on its owned technical unit which can be one of the following types:

- *inflexible producer*, i.e. a generator that physically feeds electricity into the grid and is temporally inflexible with regard to its production (like a PV plant). A corresponding agent can thus contribute a positive amount of electricity to an association which is bound to a temporally fixed time frame;
- *flexible producer*, representing a generation unit which is temporally flexible with regard to its operation (like CHP plants). A respective agent can thus contribute a positive amount of electricity to an association as well as the potential to shift the feed-in within defined time boundaries to compensate unexpected prediction failures;
- *inflexible consumer*, i.e. a consumption unit that physically takes electricity from the grid in a temporally inflexible way (like ovens or industrial production facilities). Correspondingly, respective agents can provide a negative amount of electricity to an aspired power product covering a fixed time frame;
- *flexible consumer*, representing a consumption unit which is temporally flexible with regard to its operation (like refrigerators or electric heating). Accordingly, a respective agent can contribute a negative amount of power to an association as well as the potential to shift load within defined time boundaries to compensate unexpected prediction failures;
- *storage*, i.e. a technical unit that can accumulate electric energy over time and thus physically feed-in and take electricity from the grid (like pumped storage plants). Accordingly, depending on the unit's charging status, a corresponding agent can flexibly contribute both a positive and negative amount of electricity to a product. With regard to the other unit types defined above, a storage can be interpreted as a combination of a flexible producer and a flexible consumer with an unlimited temporal flexibility.

In the context of our considerations, we generally define a bijective relationship between agents and technical units, i.e. each agent is assigned to exactly one technical unit and vice versa. Accordingly, the possible *market roles* an agent can take on in a considered scenario corresponds to one of the above mentioned types of technical units: inflexible producer, flexible producer, inflexible consumer, flexible consumer, or storage.

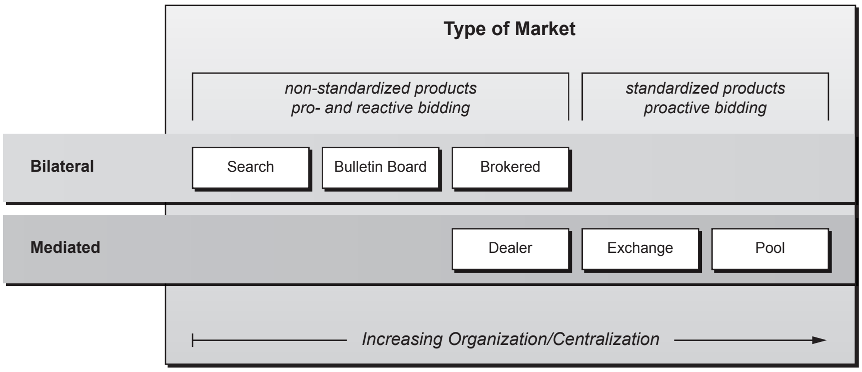

Figure 1: Market types for the trade electricity-related products (cf. [Sto02]).

With regard to the market settings in which a formation of agent associations can generally take place, Fig. 1 shows an overview on specific types of market models which can be used in the electricity domain to trade power-related products [Sto02]. As depicted, markets can either be arranged as *bilateral markets* where participants interact directly with each other or organized as *mediated markets* where products are first sold to an intermediary entity which in turn sells them to the final customer. Bilateral markets typically exhibit a less organized structure than mediated ones (with some overlap in brokered and dealer markets) but provide more flexibility with regard to contract specification as conditions can be determined individually by the respective parties. In *search markets*, buyers and sellers have to seek each other out directly in order to arrange a deal. As partially centralized search markets, *bulletin boards* allow participants to publish bids using appropriate centrally accessible media like the Internet. If trades between contractors are arranged by a third party which obtains a corresponding commission fee, the market is referred to as a *brokered market*. With regard to mediated markets, a *dealer market* constitutes the least organized type. In contrast to a broker, a dealer makes trades for his own account and sells goods with a self-defined profit margin. *Exchanges* and *pools* both represent central market platforms where participants place bids that are matched by the market itself using a dedicated mechanism. In the case of exchanges, this mechanism is given by a double-sided auction which determines a unique clearing price and allocates goods among bidders. Examples for day-ahead exchanges in Europe are for instance the EPEX Spot or the Nord Pool Spot. *Pools*, in contrast, differ from exchanges in that prices are calculated in a complex manner taking transmission capacities and grid constraints into account.

As depicted in Fig. 1, the products traded at exchanges and pools are completely standardized. In both models, participants proactively place bids on the market according to their respective capacities which are then matched in predefined time intervals. Particularly, in these types of markets participants do not react to specific offers from counterparties. Contrary, in dealer and all types of bilateral markets, participants can generally choose between proactively offering bids or reacting to already published ones by making counteroffers to requesting parties.

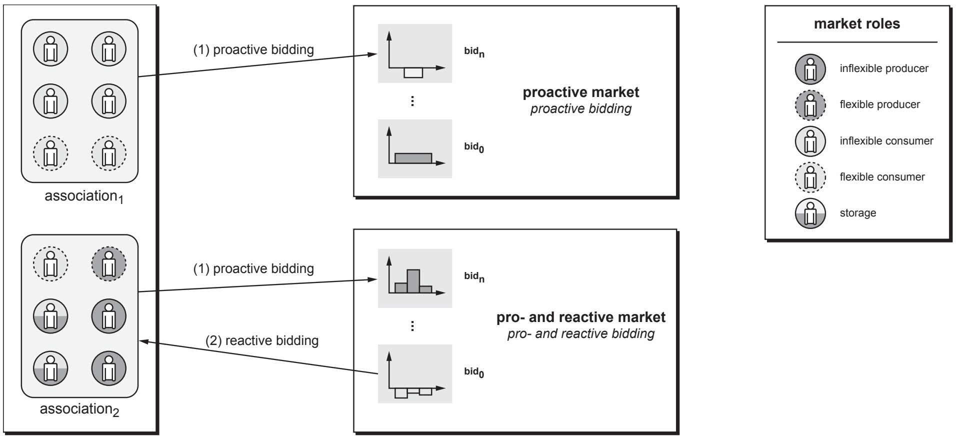

Figure 2: Considered market setting.

According to these considerations, with regard to a self-organization mechanism as proposed in this paper an agent has initially to decide whether to bid pro- or reactively before entering a formation process. This decision generally depends on the concrete market setting he is located in, but implementing both use cases – i.e. pro- and reactive bidding – provides universality in the sense that it generally allows associations to participate in each of the above mentioned market types. Thus, we derive the following two abstract market categories for the purpose of our considerations:

- *proactive markets*, where participants proactively place bids on the market which are matched by the market itself; and
- *pro- and reactive markets*, where participants can both proactively place bids and respond to offers which were already published by other actors.

Fig. 2 summarizes the above considerations by setting the specified roles and market categories in context to our work.

4 Self-Organization Mechanism for Agent Associations

Based on the market setting previously derived, the following section introduces a mechanism for self-organizing agent associations to overcome capacity-related entry barriers and form preferably competitive pools of complementing actors which allow an efficient and stable fulfillment of traded active power products. We refer to self-organization as the capability of a system to change its organization without external control, as defined in [SGK05]. Generally, we focus on spot markets where participants respond to market conditions in temporally iterative trading cycles. With regard to the drawbacks of present VPP approaches as stated in Section 1, our mechanism provides the following benefits:

- *Temporal Flexibility*. Associations form for the purpose of a single, *temporally limited* active power product. Thus, agents reorganize themselves in every trading cycle, considering past experiences and taking new local and environmental conditions into account.
- *Autonomy*. Given the characteristic of a self-organizing approach, associations form without superior control. Thus, agents completely act *autonomously* with regard to their strategic behavior, being able maximizing profits for their own account.
- *Topology Awareness*. In the context of our mechanism, associations form on the basis of a *topology-related proximity measure* which quantifies the grid-related neighborhood between agents. E.g., while participants on the same electric line can be expected to share a high proximity value, agents connected to different secondary substations would exhibit a rather low value in comparison.

The integration of a topology-related measure into the formation process provides some essential benefits. First, future electricity market are expected to increasingly include location-related aspects in their product design to handle problems arising from the increased integration of DER [BBRA10, RHS09]. Accordingly, trading associations have to take topology-related aspects into account to be compatible with such market and product designs, respectively. Second, though we focus our current work on the trade of active power products, associations might participate in the provision of ancillary services like voltage stability or reactive power supply as well. Such kinds of products necessarily require precise information about the location of participating units in the grid. Third, restricting the amount of agents in the formation process yields a restriction in the search space for the determination of an optimal partition of associations, as described below.
Using the graphical notation of Fig. 2, Fig. 3 shows the approach of an iterative, topology-aware formation of agent associations by means of an exemplary grid district. In the first instance, *initial associations* form based on their respective proximity values (3.1.1). Within each resulting initial association (3.1.2), *interim associations* form (3.1.3) using either a game theoretical or negotiation-based approach, where a representative is determined afterwards which embodies each association as a single entity. If an interim association realizes its aspired product, it is termed a *final association* (3.1.4) which is able to trade on the market and thus excluded from further formation processes. Otherwise, it iteratively enters another formation process where proximity measures are relaxed (3.2.1), thus extending neighborhood and including more agents for the formation of interim associations (3.2.2).

4.1 Problem Formalization

To specify the formation process more precisely, we start by formalizing the above described problem. As described in Section 2.2, coalition formation is a well known problem in the domains of game theory and distributed artificial intelligence. However, because we consider negotiation for the formation of associations as well, we do not adopt the exact terminology of characteristic function games but adjust it to our context.

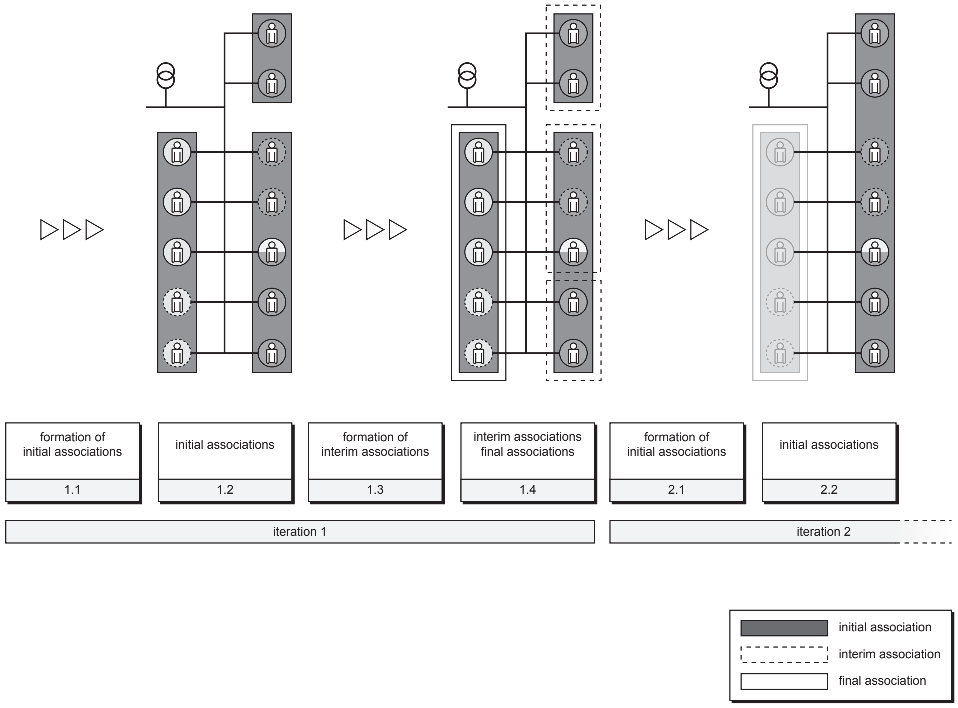

Figure 3: Example for the formation of initial, interim and final associations.

Generally, we consider a grid district on the low- and mid-voltage level comprising a set of technical units being one of the types defined in Section 3: inflexible producer, flexibel producer, inflexible consumer, flexible consumer, or storage. Each unit $u_i \in U = \{u_1, \ldots, u_n\}$ is assigned to an agent $a_i \in A = \{a_1, \ldots, a_n\}$ in a bijective relationship, U and A being the set of all units and agents, respectively. We refer to $As \subseteq A$ as an agent association and aim for an association partition $AP \subset 2^A$ such that $\forall As, As' \in AP : As \cap As' = \emptyset$. Thus, we exclude the overlapping case and allow agents to participate in one association only. The function $v : 2^A \rightarrow \mathbb{R}$ assigns a value to each association quantifying its benefit, where the overall value of a partition AP is computed as $v(AP) = \sum_{As \in AP} v(As)$. Now, the general goal of a formation process depends on the agents' social attitude: In case of an egoistic behavior, each agent strives for a maximization of its own profits, whereas in an altruistic setting actors try to maximize social welfare and thus aspire an optimal partition $AP^* = \arg\max v(AP)$.

Associations can generally trade active power products on both bilateral and mediated markets. Let $T = \{t_1, \ldots, t_n\}$ be a nonempty and finite set of distinct, successive time periods within a day. Then a bid b is defined as function $b : T \rightarrow \mathbb{R} \times \mathbb{R}$, where $b(t_i) = (e_i, p_i)$ specifies the mean amount of electricity e_i which is requested or offered in time period t_i at price p_i. Within an association, flexible consumers, flexible producers and storage can shift their bid by $\pm j$ time periods.

As an example, spot market rules of the European Power Exchange (EPEX) predefine several standardized products covering frequently traded time intervals like base- or peakload periods. In the context of this market, a time period t_i reflects a single hour of a day, i.e. $T = \{t_1, \ldots, t_{24}\}$. Accordingly, the predefined baseload block covers hours 1 to 24 whereas the peakload block covers hours 9 to 20.

Neighborhood between agents of a considered grid district is quantified by a proximity measure $prox : A \times A \rightarrow [0, 1]$, where 0 reflects minimum and 1 reflects maximum adjacency between two agents a_i and a_j in the grid. This measure can generally depend on specific characteristics of the grid like voltage level, node distances or line capacities.

4.2 Formation Process

Fig. 4 shows the proposed mechanism by means of a flowchart. Accordingly, in each trading cycle participating agents run through an iterative process comprising the following steps:

1. *Product specification.* Based on local conditions and the specific market setting (being one of the abstract types derived in Section 3), each agent has initially to determine which product to provide, i.e. which bid b to trade on the market. This includes the decision whether to trade pro- or reactively, where in the former case a new bid has to be specified which, in contrast, is already given when reacting to an already published one. While in this step inflexible producers and consumers specify the positive and negative amount of electricity they contribute to an association in a defined time interval, flexibel producers and consumers as well as storage additionally define their degrees of freedom with regard to their operation. Decisions are generally made on the basis of prognosticated values as well as experiences made in previous formation processes.

2. *Formation of initial associations.* To take topological aspects of the grid into account, agents start by forming initial associations based on a proximity measure $prox$ as described above. This formation can be either done by means of direct negotiations or through the use of appropriate registries which provide respective information about participants. To avoid a single point of failure, such registries can be deployed in a distributed manner as well. An example for a simple proximity measure would be the use of line distances between nodes in the grid, in which case shortest path algorithms could be applied to the corresponding weighted graph to determine associations with adjacent participants.

3. *Value determination.* To partition the agents of each initial association into interim associations with a preferably high benefit, the values of potential association candidates have to be calculated. Relevant criteria for their determination are for example an association's aggregated capacity potential (reflecting at the same time its market power), the degree of flexibility to compensate stochastic effects, or the amount of saved transaction costs. If a game theoretical approach is used in step 4, this equals

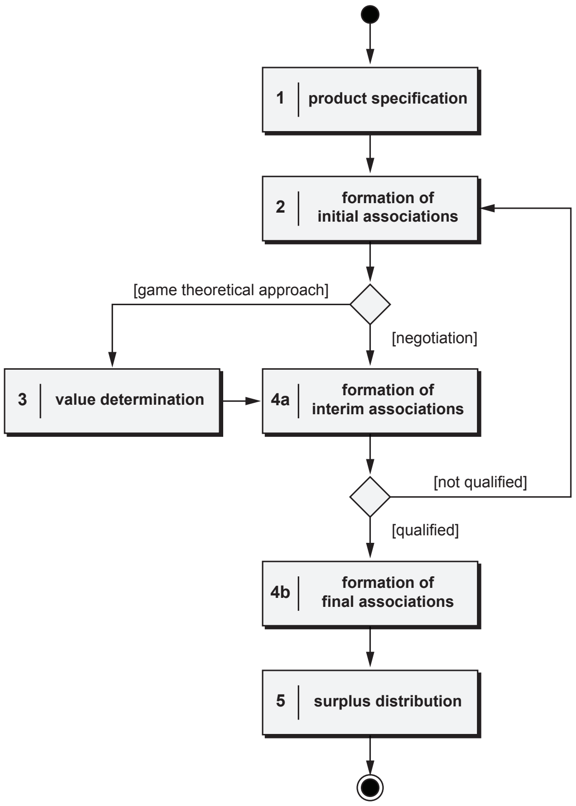

Figure 4: Mechanism for the formation of agent associations.

a specification of value function v which can be potentially done in a distributed manner using task sharing among agents. Contrary, using negotiations, agents have to determine the value directly in the course of interactions using criteria like above to decide about their cooperation on the fly.

4. *Formation of interim associations*. Within each of the initial associations built in step 2 agents form interim associations using either a game theoretical or negotiation-based approach. In the former case, concepts from cooperative game theory and DAI can be applied to determine an association partition AP which maximizes social welfare. In the latter case, agents use appropriate negotiation protocols to form preferably beneficial associations, ideally converging towards an approximately optimal solution. After the formation process has finished, a representative is determined within each association, which now has either reached its goal and is able to provide its aspired product – in which case it is called a final association – or still needs further members so it iteratively enters another formation cycle relaxing the proximity measures to extend neighborhood.

5. *Surplus distribution*. After all final associations have formed, the payoff is divided among members. Because the share of each agent depends on its contribution to a provided product, surplus distribution is associated with an association's value determined in the course of interim association formation in step 3 and 4, respectively. As experiences are used in future trading cycles, aspects of stability and fairness have to be considered in the course of the division process in order to support the repeated formation of successful associations.

Considering the two general possibilities of using a game theoretical or negotiation-based approach for the formation of interim associations, each has its own advantages and drawbacks. As discussed in Section 2.2, results from game theory and DAI can be applied to determine optimal association partitions, which are associated with extremely high computational costs, though. Approaches were proposed to reduce and decentralize calculations, but computations still become intractable when coping with larger amounts of agents. However, if initial associations are sufficiently restricted by prescribing a close topology-related neighborhood, game theoretical techniques can be reasonably taken into account. In contrast, negotiation-based protocols become appropriate when dealing with larger sets of agents, sacrificing the possibility to determine a globally optimal solution. I.e., results from negotiations can be arbitrarily worse than the optimum as participants do not maintain a complete model of their environment. Moreover, even negotiation-based approaches are limited by an upper bound of agents because communication costs grow with an increasing number of actors.

Thus, in the course of association formation the crucial factor for the choice between both approaches is given by the size of initial associations. Accordingly, agents might apply game theoretical concepts when the amount of participants is sufficiently low and switch to negotiations when the set exceeds a certain threshold.

5 Conclusions

This paper introduced a self-organization mechanism for autonomous agents in electricity spot markets enabling participants to overcome capacity-related entry barriers and optimize the competitive provision of products by aggregating and complementing their capabilities. The approach particularly allows actors to respond to short-term market conditions by forming associations in a temporally flexible way and supports an efficient supply by taking topology-related aspects of the grid into account.

Presenting the general framework for the formation process, several aspects have to be addressed in future work with regard to the described process steps. First, criteria have to be determined which allow an appropriate assessment of an association's value. Moreover, reasonable measures are needed to quantify the grid-related neighborhood between agents. With regard to the formation of interim associations, appropriate concepts have to be developed which allow an efficient but still tractable coordination between agents, potentially integrating results from the domains of game theory and DAI. Finally, methods for surplus distribution are required which consider fairness and stability to support the repeated formation of efficient associations in the future.

The conceived self-organization mechanism is to be validated in an agent-based simulation evaluating the different concepts with regard to aspects like individual and global economical efficiency or computational tractability. In particular, the interplay of game theoretical and negotiation-based approaches will be focus of interest.

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