PhD Proposal: Reservation Exchange and Dynamic Pricing & Procurement

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Highlights: @ A continuous double auction market with a new type of limit order books is proposed to replace incumbent electricity families, making it possible for small-scale prosumers to directly participate. @ Discrete event simulations of multi-agent systems are used as the main research tools to demonstrate market operations and decision-making processes. @ A new decision-making framework based on model predictive control is introduced to facilitate procurement, control and response of participants. @ Based on the same idea, a business as retailers can be started up in incumbent power industries as real-world experiments. Existing literature in revenue management, inventory management, supply chain management, etc can be put into use. @ Simulations can provide statistics for long-term investments, and a new structure for power systems can emerge, especially in underdeveloped areas. @ The market can be applied in other industries, like food supply chains, the retailing and the banking.

1. Aim and Novelty

In the power industry, it is urgent to reduce the carbon emission from power generations, avoid backup generators and penetrate modern power systems. Other industries, like food supply chains, face similar challenges. The lack of direct participation from the demand side is the central question, which may be solved by the market designed in the project. Arguments for these designs can be established in two stages:

- Because of the complexity, in the first stage, simulations instead of analysis are primarily used to demonstrate how the market operates and prosumers make decisions under different settings. To facilitate the simulation of participants in the market, a new decision-making framework is defined. The objective is to establish the most realistic simulation toolbox by trying candidate models and conducting computer experiments.
- In the second stage, a new retailing business with similar features can be set up and field-tested in incumbent power systems, of which the results can be used to examine key assumptions and calibrate simulation models. With validated simulation models, new structures for power systems can be proposed.

The necessity for the new market is discussed in section 2, followed by the description of the market in section 3. The methodology is discussed in four parts of section 4. The first part introduces the simulation schemes used, and the second part discusses the core simulation programs. The project can be researched from three perspectives, which are listed in the third part, and the most important one is elaborated in the last part. Expected contributions are summarized in the last section.

2. Background and Motivation

Small-scale producers/consumers (**prosumers**) parag2016electricity prefer entering into contracts to isolate themselves from the vagaries of wholesale markets, so their participation is mediated by retailers, who take the risk and profit from premiums. This strategy is widely applied in industries with durables, while is impractical for fresh foods and electricity because of their continuous generations/consumptions, reliance on **delivery networks**, and time-dependence. Retailers must face price spikes from time to time because they are obliged to satisfy the needs of their customers. kirschen2003demand

Instead, mechanisms satisfying the following requirements should be applied:

- Adaptive to external factors temporally and spatially. For example, time-varying peak loads resulted from penetration of renewable generations exclude applications of traditional load shifting or shedding. connell2014benefits
- The market should be as transparent as possible, while private information is tightly protected. Neither centralized command-and-control nor retailing is efficient in such settings because of the conflict between better market clearings and information protection. kirschen2018fundamentals It is prosumers who anticipate their future states, formulate trading strategies and act accordingly.
- Low-cost. Coordinated demand response is essential to ensure the quality of energy supply when none of the advanced technologies, like large-scale storage, hydropower, nuclear power, can be relied on to balance power systems in underdeveloped areas. jacome2019power
- Purchases should be ahead of deliveries prasad2011advance, because the spot selling season is infinitely small. The real-time incentives from spot markets are hard to catch, because not only the current signals can hardly reveal any information about the future, but also prosumers need time to adapt their activities to fit traded quantities. kirschen2000factoring
- Transactions can be instantaneous because some prosumers arrive randomly and may demand liquidity. foucault2013market Also, some would like to trade for long periods covering many trading units to save the trouble from making decisions regarding few units but in high frequency.
- The market is thick enough but not congested, so prosumers do not have to search or bargain. In other words, the market is liquid enough for prosumers to lower transaction costs.
- The number of statistics for decision making is as low as possible but different assets can be distinguished based on those statistics.
- The imbalance within trading units can be maintained without centralized system operators kirschen2018fundamentals, because it may be hard to establish trustworthy regulatory authorities and operators responsible for the system safety.

Till now, all market designs fail to fulfil these requirements, while in this project, at least one capable market is brought up. The most promising candidate so far is introduced in section 3, following discussions about its primary function, traded assets, two features, and superiority over others.

3. Proposed Solution: Reservation Exchange

The proposed solution is a **continuous double auction** market with **3-dimensional limit order books**, where prosumers can bid/offer continuously and get transacted once matched with another order. It allows immediate transactions and standby orders at the same time. Similar to computerized reservation systems in airline industries, prosumers have to book before the delivery, and markets are segmented according to when bookings are made. shy2008how Therefore the market is named **reservation exchange (Rex)**. With delivery networks integrated, the whole system is named **RexNet**. [1] For power industries, Rex can be used to replace the market families including day-ahead market, intra-day market, balancing market, capacity market and other ancillary markets.

The most important function of Rex is **quantity discovery**, which is similar to price discovery in limit order markets for financial assets when markets motivate participants to reveal their private valuations. maloney2003complexity Two kinds of discoveries can be generalized as dynamic equilibrium discovery, which creates knowledge by incorporating dispersed information at high speed. birchler2007information Likewise,

[1]Two names are used interchangeably.

prosumers are encouraged to take advantage of their information about the aggregated prosumptions in Rex, so mismatches can be eliminated in high speed without the necessity for centralized monitoring.

Traded assets in Rex belong to **time-dependent products (TDP)**. Different kinds of service always involve producers and consumers at the same time, making it the majority of TDP. Some settings have been introduced to convert electricity into tradable TDP and differentiate them temporally and spatially.

In this project, all kinds of delivery networks can be divided into two levels: distribution networks (whose constraints can be ignored) and transmission networks. The market is **spatially fragmented** by transmission networks when relevant edges are congested, so stakeholders in control of transmission networks can participate in Rex as spatial arbitragers. Moreover, Rex can be established **hierarchically**. Representatives of prosumers in lower levels can serve as retailers, which makes the experiments in subsection 4.4 plausible.

Though the structure of Rex is similar to that composed of day-ahead markets and intraday markets, the main difference is that there is no one responsible for satisfying uninformed demand of prosumers in Rex. For example, utility companies are not obliged to satisfy demand in peak hours. If **reservation** and **realization** does not match, he/she has to take the consequence. Thus, there is no need for centralized managers to maintain system safety. So despite the similarity, methods in nair2014energy and secomandi2014optimal are fundamentally different from those in this project.

Also, trading volumes in intraday markets are insignificant compared to those in day-ahead markets and balancing markets weber2010adequate, so most of the current researches focus on periodic double auctions used in day-ahead markets. Approaches to Rex deviate from these researches, and decision-making processes are different as well.

With only one type of agents (prosumers) providing and consuming liquidity, Rex is an **order-driven continuous double auction market** in essence. gould2013limit There are many variations like quote-driven markets, where market makers are the primary source of liquidity. As discussed in section 2, it may be hard for small-scale prosumers to participate if the market is not the most simple and flexible one, making Rex the focus in the simulation stage. With adequate data and assumptions validated in the second stage, better options may be identified.

4. Methodology

Models and methods in the simulation stage will be elaborated first in subsection 4.1, then the decision making framework of prosumers is introduced in subsection 4.2. Some specific simulation programs are presented as well. In subsection 4.3, three different ways to analyze Rex are discussed. Finally, field experiments in the second stage are outlined in subsection 4.4, and some key differences from models in the literature are emphasized.

4.1. First Stage: Discrete Event Simulation of Multi-Agent Systems. Take energy systems, especially power systems, for example, they can be represented by the figure 1-a, summarizing the supply chain from extractions to end-uses, of which the key stage is the distribution from the supply side to the demand side. blok2017introduction Alternatively, the system can be restructured by figure 1-b by introducing Rex. Prosumers can be modelled as three parts.

- **Clients** are used to simulate the ultimate needs of the prosumer like minimum requirements of room temperature in winter. They are assumed to report their forecasts unreservedly, despite imprecision before the realization.
- **Continuous provision plants (CPPs)** are underlying physical and/or economical systems with inputs (electricity, sunshine, water, etc) and outputs to meet the needs of clients. For example, it can be an electricity-driven heat pump and pipes for space heating. Usually, there is inter-temporal dynamics within these systems, so the framework in subsection 4.2 is required.
- It is **coordinators** who control CPPs and participate in Rex, and their objectives are to make more profit (or lower costs), satisfy needs and respect constraints at the same time. The direct participation of small-scale prosumers discussed in section 2 is a critical premise for this structure so that there is no friction between these three parts because they refer to the same prosumer.

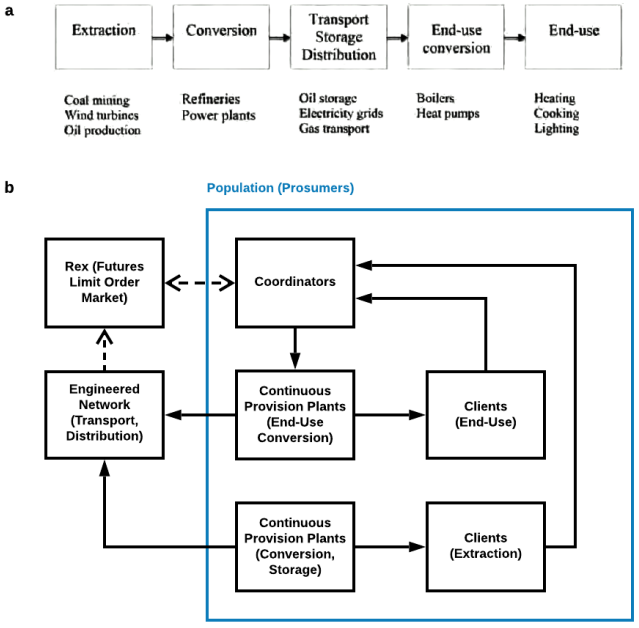

Fig. 1. Two ways to represent energy supply chains. (a) Illustration of energy supply chains. (b) Restructuring of the chains based on Rex.

In this project, we are interested in both the market and prosumers, which therefore have to be modelled as **multi-agent systems**, because prosumers have diverging information and interests. shoham2009multiagent No centralized manager knows all variable outcomes and controls everything, so the market clearing process needs to be optimized in a distributed manner. This structure distinguishes this project because researchers must model heterogeneous prosumer instead of formulating a management strategy.

Hence, **agent-based models** are used iori2012agent, lebaron2001builder, and their interactions through Rex are demonstrated by **discrete event simulations**.

4.2. Decision Making Framework for Prosumers. The simulation timeline can be summarized as follows. Some clients, like wind turbines in power systems, are endowed with prosumptions, the quantity of which are simulated with similar patterns to historical data. Because they don't know the precise quantity in advance, they will forecast based on their private up-to-date information, the outcomes of which are simulated as well. Once their forecasts update, they will convey the differences to coordinators, who are obliged to react to it before gate closures. For the sake of privacy protections, high-resolution models of CPPs are known to corresponding coordinators only. Future outputs can be predicted from CPP models and planned inputs. Then, coordinators modify plans, participate in Rex and cooperate with clients.

The decisions can be optimized by **receding horizon plan & order management (RHPO)**, which has similar structures to model predictive control problems. rawlings2019model After deciding trading volumes, coordinators have to manage **make-take decisions** according to order flows, states of limit order books, foucault2013market and their private evaluations of their positions. **Position** is the difference between the market total volume and fundamental volume. The precision of evaluations differs among prosumer., so quantities are discovered because informed prosumers communicate their high-value information by trading aggressively. Overall, the states of Rex are changed instantaneously at separate time points when some coordinator submits order according to its RHPO instructions, making the discrete event simulation a reliable method.

Here are some prototypical stochastic simulation programs used in this project:

- To simulate realizations, like those from wind turbines, at new locations according to historical data, statistical methods in the frequency

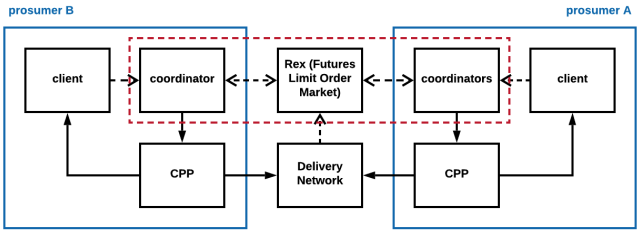

Fig. 2. Illustration of three ways to analyze Rex

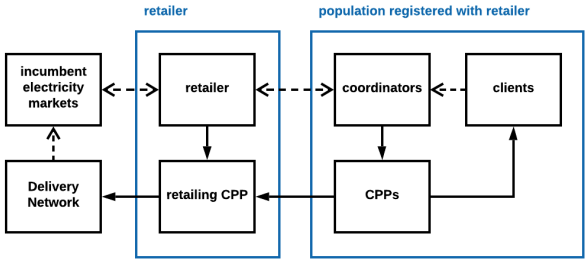

Fig. 3. Illustration of new businesss as retailers incumbent power systems

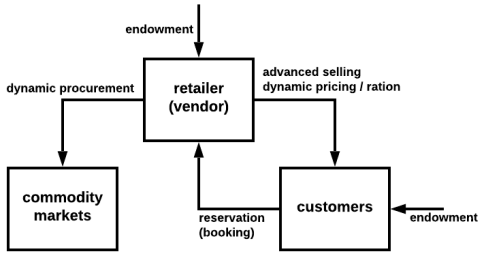

Fig. 4. Illustration of the new businesss using terminologies from relevant literature.

domain can be utilized to exhibit the spatial diversity and make use of available information as much as possible. woods2013simulation

- To simulate evolutions of discrete states in a bottom-up way, inhomogeneous Markov chains can be constructed using detailed survey data. page2008generalised For example, electricity consumptions of residents associated with their occupant presences can be obtained.
- Martingale models of forecast evolution can be used to simulate requests sent to coordinators. heath1994modeling
- CPPs may correlate with each other so they must be modelled by an aggregated CPPs controlled by one coordinator to satisfy several clients. For example, the space heating system for multi-dwelling buildings must be modelled by multi-input-multi-output control systems. siroky2011experimental Moreover, retailers can be introduced to form a hierarchical Rex, which will be discussed in subsection 4.4.
- Grey-box modelling techniques, which combine statistical methods and physical knowledge, can be used to identify CPP models. bacher2011identifying

4.3. Three Ways to Analyze Rex. There are three angles to this multi-agent system, which are illustrated by figure 2.

- The first one is from coordinators, and it includes three elements for prosumers like those in two solid blue boxes.
- The second one is to focus on the evolution of Rex and it includes coordinators only, which is shown by the dashed red box. The induction of stylized facts of Rex is the primary task, which makes it possible to simulate the market directly. buchanan2011it Then the effect of different resolution parameters, introductions of market makers, replacement with periodic double auctions, etc may be explored. It also provides opportunities for researchers with the first perspective to tune parameters.
- Last but not least, a holistic view including all models is necessary, because key features of Rex, like the shift from quantity-based to power-time-based cost allocation hougaard2009introduction, must be examined this way. The quantity discovery function must be demonstrated in this way as well.

4.4. Second Stage: Dynamic Pricing & Procurement. New business as retailers in incumbent power systems can be field-tested in the second stage. As discussed in section 3, Rex can be established in a hierarchical structure, so retailers can be introduced to as another layer between prosumers and the market, which is illustrated by figure 3. Prosumers still need to reserve via the retailer instead of Rex. In this setting, retailers face a **continuous forward dynamic pricing & procurement (CFDPP)** problem. The implementation of the retailing business and the analysis of customer behaviours are the primary concern, so there is no need to establish the whole market.

Lots of existing literature can provide insights into CFDPP:

- Newsvendor's procurement. qin2011newsvendor Dynamic procurement can be utlized when there are multiple decision epochs. wang2012multiordering
- Forward dynamic pricing of TDP. The initial inventory is endowed without cost considered in contrast to that in the previous category. Most of the techniques are from revenue management. gallego2019revenue
- Inventory management of perishables. nahmias2011perishable
- Dynamic pricing of durables. ahn2007pricing When strategic behaviours of customers are endogenous, game theoretical models should be used. su2010intertemporal
- Advance selling from the perspective of retailers and reservation (booking) from the perspective of customers. shugan2000advance Much literature focuses on how to deal with strategic customers. prasad2011advance, zhao2010pre

Essential terminologies from the above literature are illustrated using figure 4. There are some highlights:

- Prosumers do not know about their endowments or utilities for sure at reservation decision epochs. shugan2000advance
- Regarding demand, the conservative approach is to assume that it is either satisfied (leading to sales) or lost forever, and there is only one product in the market. shen2007customer Instead, a continuous manner must be adopted to tackle inter-temporal decisions, for which RHPOs are designed.
- Outcomes of random variables are always assumed to be known to everyone immediately in existing literature su2010optimal, ignoring the discovery process.
- Procurement costs in future epochs are stochastic.

Key assumptions in simulation programs can be evaluated using the experiment results. Besides, it is vital to validate simulation programs based on measured data. ross2012simulation For example, simulated forecast evolution should be analyzed according to standard analytical tools for forecasting madsen2005standardizing and compared to results from state-of-art forecast techniques.

5. Expected Contributions

The assumption of time invariance can be relaxed once short-term models are mature. The existence of investments, ageing and accidents brings about more randomness and flexibility. spyrou2019planning Usually, massive long-term infrastructure investment is required in power industries. Simulation results from Rex indicate investment opportunities. The ultimate goal of this project is to formulate a new structure for resilient, low-carbon, low-cost energy systems based on Rex.

With simulation methods validated, Rex can be applied in other industries like food supply chains, retailing, banking, etc. Besides, similar assets can still be pooled, when personalized limit order books are introduced to find matches with requirements satisfied from both sides. The process is similar to that in peer-to-peer markets with bilateral trade agreements. sousa2019peer

All in all, following problems are expected to be solved:

- The effect of reservations on responsive clients, who can adapt their needs to current states, is not clear. It may be modelled by an intrapersonal game where a decision-maker is summarized by a succession of selves brocas2009dynamic or joint workings of time inconsistency & consciousness. birchler2007information
- When optimization problems in RHPO are formulated nonlinearly, it may be hard to obtain shadow prices, which indicate costs of flexibility and responsiveness.
- Agent-based models should be able to learn and adapt to evolving situations. franklin1997it
- The determination of weight matrices is the challenge faced by MPC researchers as well rawlings2019model, and the tuning relies heavily on methods discussed in subsection 4.3.
- How to make Rex robust to external factors.

As discussed above, the project can be divided into two stages. Expected outputs of simulation experiments in the first stage are:

- Introduction to Rex. (my DTU master thesis)
- RHPO for more complex CPPs, like those with stochastic MIMOs, and their statistical identification methods.
- Rex with responsive clients.

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