An Agent-based Modeling and Simulation Approach to Commodity Markets

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Abstract

The present work provides an open source, agent-based behavioral model primarily addressed to the dynamics associated with the commodities spot price formation, as well as variations and contrast patterns belonging to the exchanged quantity. The framework can flexibly be used for several commodities, but it has to be integrated and qualified with the modelization of producers' and buyers' behavior when used for the analysis of a specific commodity, stock or group of merchandise. Due to the fact that various commodities or consumer artefacts are perceived and treated differently in several diverse contexts, the intended tasks or functions are mainly entrusted to those experts in the specific fields who would find the software tool we designed a good starting point for their investigations. Toward achieving this aim, an open source code is provided and a detailed documentation on how to use, further develop and enhance the present features of the proposed agent-based modeling and simulation software is publicly available at https://github.com/gfgprojects/cms.

keywords: Agent-based Model, Commodity Markets, Commodity Price Dynamics, Food Security, Open Source Software.

Introduction

The study of commodity markets is an interesting field for several reasons. The first is the role played by agriculture products in feeding living beings, because it directly impacts on the possibility of a part of the world's population to survive (van der Mensbrugghe, 2009). As witnessed by the 2007/08 world food crisis, the high increase in price observed in these years heavily reduced the access to food by poor countries and lowered the possibility for them to receive help from aid agencies (Wiggins and Levy, 2008). Second is the role of commodities as an input for real production activities (Li et al 2017). This heavily impacts on the macroeconomic performance, which is perhaps a less urgent issue than that of survival, but nevertheless affects the standard of living of the whole population. Significant examples are provided by effects of crude oil price fluctuations on economic activities and on people's everyday lives. Third is the growing interest in commodities markets as financial investments. These new markets widen the possibilities of financial operators to diversify their portfolios, hedge against risk and speculation. Therefore, noncommercial trading is gradually growing over time (Mayer, 2009).

Studying this field is also interesting because of the considerable diversity among commodities. Besides the standard taxonomy – metals, energy and agriculture (see Bain, 2013, for example) – features such as seasonality in production, demand and the storable feature of the production present challenges to the researcher. On the other hand, commodities have the common feature of being produced in a number of different places around the globe, and of being exchanged in international markets and then moved from the place they are stored to places where they will be employed. In other words, commodities are globally traded goods.

The aim of this work is to provide a model that accounts for these common features and that is able to handle the producers-buyers relationships in international markets.

Before going on with the model description, we think it is useful to provide a short overview of the field of interest to describe techniques and tools employed in the analysis. This will allow us to highlight objectives and motivation of our work.

A large part of the literature deals with the explanation of commodity price dynamics.

A comprehensive review of this research is provided by Labys (2006). Labys shows how scientific problems and modeling strategies change with the time horizon the researcher is dealing with. Identifying changes in price trends, detecting structural break and establishing the convergence of prices in various geographic regions are the main issues in the long run. The econometric model of interest in this case is "those dealing with structural breaks, booms and slumps, secular movements, and risk analysis" (Labys, 2006, p. 3). Spectral and dynamic factor analysis and structural time series models are instead employed to analyze cycles in commodity prices in the medium term. Short term prices move erratically, and the main effort here is to identify the stochastic or non-linear processes able to better replicate fluctuations. The most advanced econometrics techniques (such as ARIMA, ARFIMA, VAR, ARCH, GARCH, etc.) can be used to model and forecast primary commodity prices in this case.

The state of the art of commodity price modeling is also reported in Pirrong's work (2012). Pirrong's work is relevant because in addition to bringing a significant contribution to the field by using a combination of advanced theoretical and computational techniques, it instills the idea that much other progress is possible and, especially, that real world data are the definitive guides and arbiters for theoretical modeling. However, "the empirical data show that real world commodity price behavior is far richer than that predicted by the current generation of models" (Pirrongs, 2012, p. 4).

The approaches that we have just described are intrinsically dynamic and convey the idea that the systems under investigation are in continuous motion. This is also because the analysis focuses on prices, which is the most flexible of economic variables.

A totally different perspective supports the market equilibrium approach. In the absence of significant exogenous shocks, the motion of the system is thought of as smooth because market forces drive the variables to their equilibrium levels. It is therefore valuable to gain a detailed knowledge of the equilibrium, a state in which the system spends a large portion of its time.

Considerations of quantities are an important part of this detailed knowledge. Therefore, market equilibrium models give more importance to quantities than the time series approach previously discussed.

The market equilibrium approach usually accounts for the presence of several markets. Because economic agents can act simultaneously in a number of them, all markets end up being interconnected. As is well known, the goal of the analysis is to find prices and quantities which ensure a simultaneous equilibrium in all the considered markets. In this respect, models are classified according to the elements of the economic system they account for. Partial equilibrium models generally focus on a sector of the economy. General equilibrium models strive to include all the relevant sectors and economic actors.

A further step in this process is represented by models accounting for several economies and the interaction among them. These models are also employed for the analysis of global trade. The Global Trade Analysis Project (GTAP) is a reference point in this scenario (https://www.gtap.agecon.purdue.edu). Both partial and general equilibrium models are used in this kind of analysis (Meilke et al, 1996; Francois and Reinert, 1997; van Tongeren, 1999).

From the technical point of view, finding the simultaneous equilibrium of a number of interacting markets means solving a system of equations representing demands and supplies balances in all markets. The possibility of obtaining an analytic solution is suddenly lost when the dimension of the system increases. Therefore, computational techniques are normally used to obtain solutions. Indeed, their use fostered the important stream of economic literature labeled Computable General Equilibrium modeling (Fullerton, 1990; Francois and Martin, 2013; Burfisher, 2016).

The present work tackles the study of commodity markets using a different computational approach: agent-based techniques.

The overview provided above gives the basic elements to understand the motivation for this choice. First of all, the intent is to build a tool to analyze both the prices and the quantities in a system of markets. In this respect, the model's aim is close to the market equilibrium approach. However, the bottom-up process underlying agent-based modeling provides two important opportunities. First, it is not necessary to impose the equilibrium conditions in order to compute prices and quantities. Second, the resulting model has a more dynamic nature, being able to account for more "active" systems. In this sense, the analysis of prices can be performed in a setting similar to that envisaged in the time series approach commented above. Furthermore, the agent-based approach gives the possibility to enrich the model with varieties of agent behavioral types at the microeconomic level. These heterogeneous behaviors can concern different time scales so that in this sense, the model is more flexible than other modeling strategies.

Related Works

The use of agent-based models has been blossoming in recent years in various disciplines. Concerning commodities, works mainly focus on the opportunities they offer for trading and financial management (Cheng and Lim, 2009; Zhang and Wu, 2014). These papers, however, have a different aim from this work. As explained in the introduction, our aim is to provide a tool to analyze prices and quantity dynamics in a system of multiple interacting markets. It is not easy to identify similarities in the plentiful and growing set of agent-based models. A useful piece of help in this task is the work of Abar et al (2017), who provide a wide review of the available agent-based software. None of the 85 agent-based simulators surveyed by them show similarities with the model presented here. Therefore, to the best of our knowledge, this is the first example of an agent-based model aiming to analyze markets of globally traded goods.

At present, the computational model closest in spirit to ours is a simulation tool provided by the World Integrated Trade Solutions (https://wits.worldbank.org/simulationtool.html. It is a spreadsheet application which determines international prices and trade flows of a chosen industry using the market equilibrium approach. The aim of that application is to evaluate the effects of global trade policy changes at the industry level comparing the equilibrium situations before and after the policy change (Francois and Hall, 2003).

The model presented in this paper has the advantage of being intrinsically dynamic. Beyond the dynamic of prices, it can be used to analyze the evolution of the international trade network of a particular industry or product after a shock or a policy change. The analysis of trade networks is a topic of recent research (Barigozzi et al. 2010; Fair er al. 2017). Another recent application of agent-based techniques that uses trade networks is freight transport (Holmgren 2013, Abed 2015). Therefore, the model presented here has potential applications in these fields.

We think the model presented here could be enriched in the future in order to analyze more general issues, such as food security, climate effects, business cycles and related policies at the macroscopic level. Some agent-based models going in this direction are described in Crooks and Wise (2013).

Software Overview

The software is named “Commodity Market Simulator” (CMS). It is developed in Java on top of a general purpose agent-based modeling system: Repast Simphony (RS) (https://repast.github.io).

This architecture provides significant advantages to the users who can exploit RS facilities for scheduling, data recording, graphical elements production and running the model in graphical and batch mode, both in a single machine or in parallel using remote computational power. Users can therefore direct efforts uniquely to the modeling of agents behaviors and their interactions. In addition to the aforementioned facilities, we choose RS because it is free and it has a wide user community and an active development and supporting team.

The goal of this research is to provide a tool that other researchers can customize and develop. The implementation is therefore general and not oriented to any particular commodity. Moreover, in order to reach the largest possible diffusion, the CMS source code is available in the following gitHub repository: https://github.com/gfgprojects/cms. At the previously given github URL, the interested reader will also find documentation providing a detailed description of how to get the CMS running and of how to customize the model. A particular effort was made to provide such documentation following Muller et al (2014) recommendations.

To allow the reader to understand at a glance the type of modeling that is made possible by the current version of the software, Figure 1 is provided.

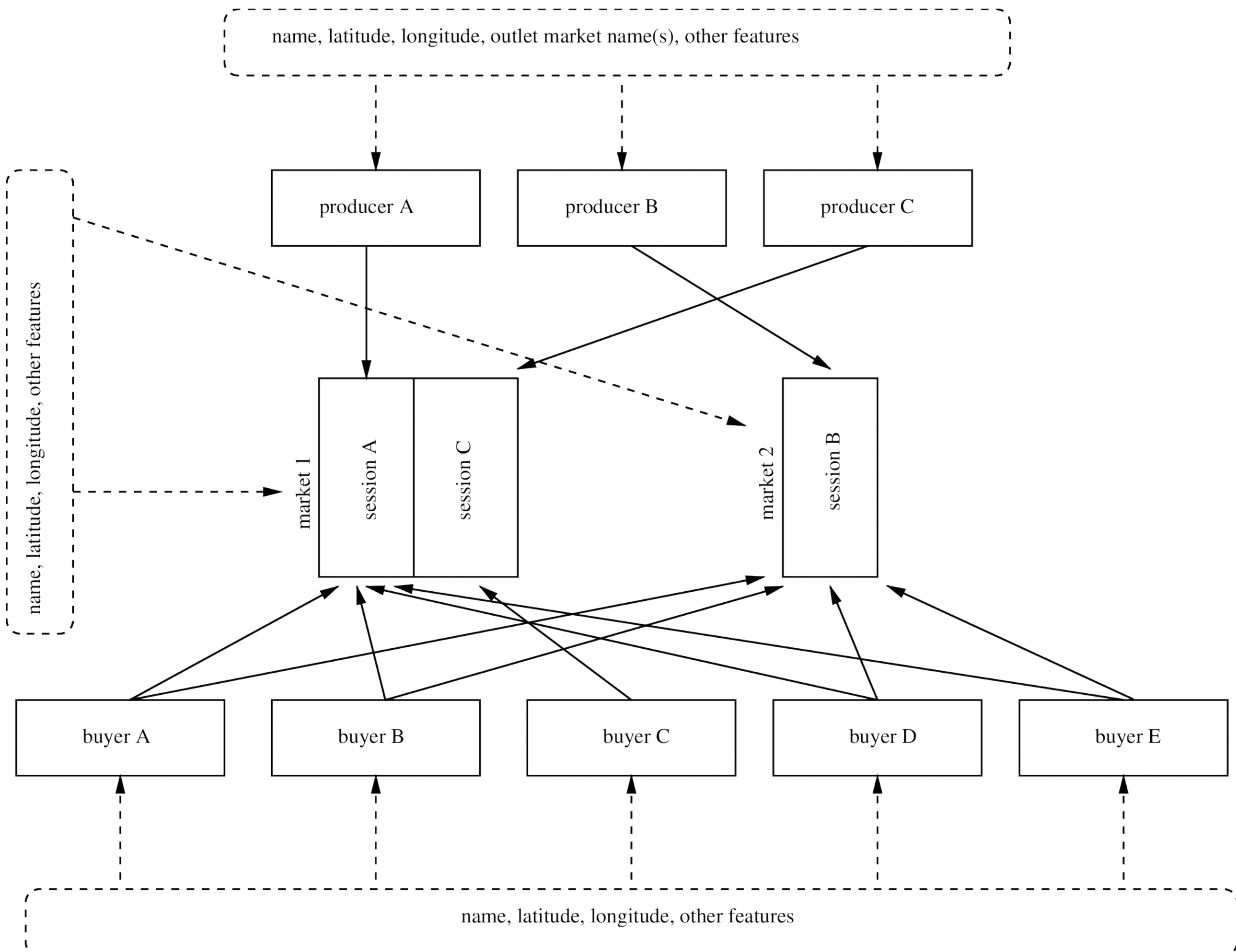

Figure 1: diagram of a model that can be implemented by the current version of the software. Dashed lines denote inputs needed to configure and run simulations.

As can be easily understood from the figure, the model consists of a framework for producers-buyers-market interaction. In the figure, there are three producers (A, B and C) and five buyers (A, B, C, D and E), who interact in two markets. We do not here give a detailed explanation of this diagrammatic representation, because several reference to this figure in the following text will explain it in detail. However, it is worth noting that the dashed lines in the figure denote inputs needed to configure and run simulations. The number of buyers, sellers and markets, as well as their features, can be controlled by the users in three dedicated configuration files, named producers.csv, buyers.csv and markets.csv. As explained in the software documentation, each line of these files contains inputs to create an agent. Each line's content changes with the type of agents; however, the agent's name, latitude and longitude must be specified at the beginning of the line for all agents. The producers.csv file needs additional information concerning the market(s) in which the producer sells the product.

Several comma separated values (csv) files collect data from each simulation run. They record figures for a number of variables: prices and quantities exchanged in the market(s), the quantity bought by each buyer in each market, the total quantity bought and the gap to the desired or needed quantities, as well as the quantities sold by producers. We point the reader to the illustrative example given below for a more detailed understanding of the software outputs.

Figure 2 concludes this section by showing the software graphical user interface (the figure is not related to any real world commodity).

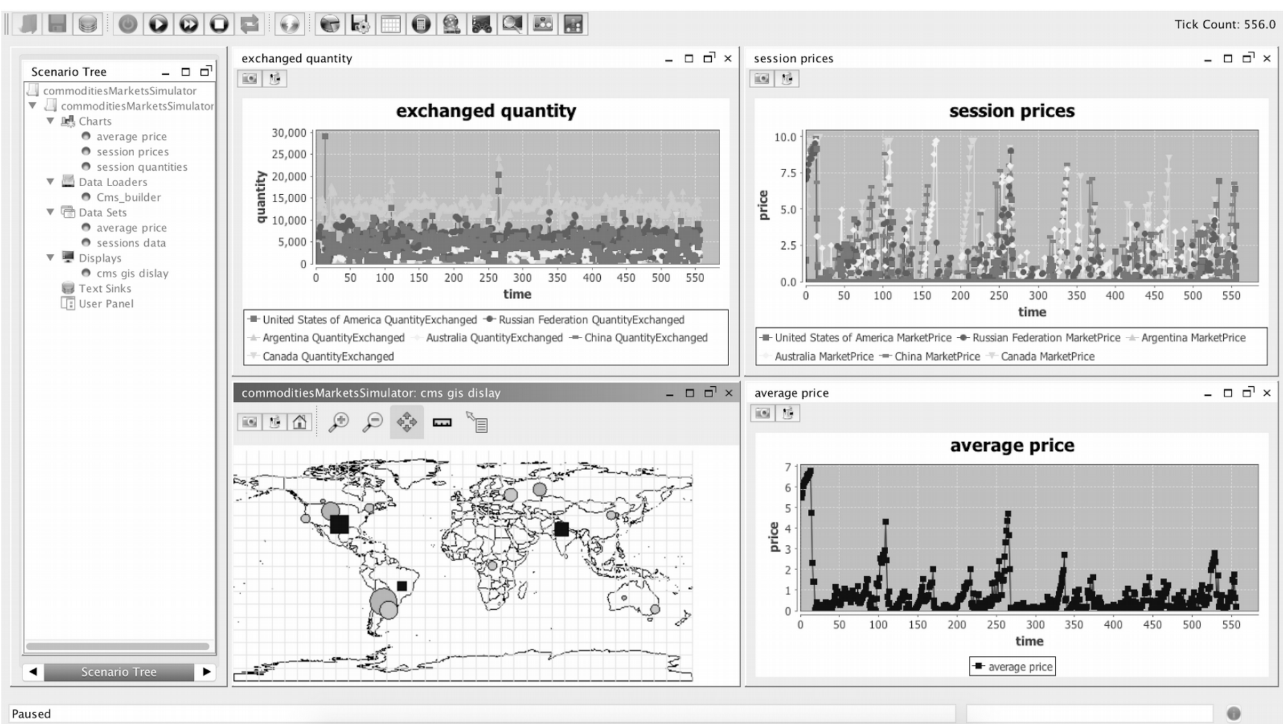

Figure 2: screen shot of the software graphical user interface.

Software Framework

The CMS has three types of agents: producers, buyers and markets. The agents' common feature is that each of them has a geographic location given by a latitude and a longitude. In the most straightforward interpretation, agents can be thought of as sovereign countries, but it is possible to set up the model to conceptualize different geographical scales, such as continents, macro areas or regions of a country. For the convenience of exposition, we will hereafter identify producers with countries. However, the user can design different scenarios given that the model is fully customizable. The setup is as follows:

- if a country produces, it also uses the resource;
- the resource can be used by a country that do not produce it;
- the number of markets and their geographic location is independent from the number and location of producers and buyers.

Figure 3 can be used to clarify these statements.

Figure 3: the map shows producers (dark grey circles), buyers (light grey circles) and markets (black squares).

This figure displays the same setting showed in figure 1. There are three producers (dark gray circles), five buyers (light gray circles) and two markets (squares). The commodity is produced in A(rgentina), B(urundi) and C(hina). These countries also use the product. This is why the map shows the presence of both a buyer and a seller in these three countries. In addition, countries D(jibouti) and E(cuador), which do not produce the good, demand the product. The figure also shows that the bargaining for the commodity is carried out in two markets: Sydney and Brussels.

We will hereafter focus on the market organization, which allows for an overall understanding of the model functioning. We point the reader to the software documentation for additional details on agents' configuration and behavior.

Market Organization

Considering modern information and communication technologies, we model markets as (virtual) places where producers and buyers send information. More trivially, resources are not physically moved to the marketplace by the producer and, once sold, moved again from the marketplace to the buyer's place. As commonly happens, buyers and sellers send their offers and orders to the market. The market uses this information to reach an agreement. Once it is reached, the resources are directly moved from the seller's place to that of the buyer.

When the model has more than one market, the opening order is set according to the starting time of economic activities in each market location (longitude provides a proxy of it).

Markets are organized in sessions. Each market session is directed by a producer. A producer can have only one session in a market and must participate in at least one market. This organization allows buyers who bid in a given session to know who is the producer of the goods s/he is buying. The producer's geographic location has an important role here because it informs buyers on where the resource is stored. Because it is assumed that buyers bear the transport costs, the proposed market organization allows buyers to compute such costs and account for them when submitting bids.

Market Participants

A producer can decide to sell exclusively to a buyer in his country. In the real world, this happens when a country forbids exports. Similarly, a buyer who has a producer in his country can decide to buy exclusively from him (a producer country can forbid imports). The latter is not possible if the buyer considered does not have a producer in his country (a non-producer country does not forbid import). Summing up, market session participants are:

- the producer who directs the section;
- the buyer in the same country as the producer;
- foreign buyers, if the two following conditions are both satisfied:
    - the producer allows exports;
    - the foreign buyer allows imports.

We can again use Figure 1 to provide a real-world projection. In the model presented in this figure, producers A and C organize a session in market 1, while producer B organizes a session in market 2. Focusing on the arrows exiting from buyers, we understand that country C forbids exports or imports, hence the session is attended only by the producer and the buyer in this country. No restrictions are imposed by countries A and B, whose sections are not attended only by the buyers in country C.

Dynamics

The "cornerstone" of the dynamics is the simulation time step. In each simulation time step, several actions can happen, however, what mostly characterizes it is that all the market sessions are performed. This provides a link between real and simulated time: if we want to simulate a real-world situation where markets operate once a day (week, month and so on), a simulation time step represents a day (a week, a month and so on). Staring from this observation, we can comment on the other simulation events. Consider, for example, the dynamics of a storable commodity. Straightforwardly, at each time step, each buyer's inventories are increased by the sum of quantities bought in the market sessions it attended, while each producer's inventories are decreased by the amount sold in the market sessions it directs. Knowing the time scale is important for modeling the opposite flow. For buyers, the opposite flow to purchases is consumption. Therefore, if a simulation step represents a day, we have to take into account daily consumption. Modeling the opposite flow is more tricky for periodically produced commodities, such as agriculture products. The opposite flow to sales is production, but if we take as an example yearly produced commodities, we do not have a quantity that is produced daily, weekly or monthly, as we do for continuously produced commodities. The simulator can account for this periodicity: It gives the possibility to adapt the frequency of the production flow to the model time scale. Consider, for example, a situation where a time step represents a month, and the production cycle is a year. In this case, during the setup phase, the researcher chooses to increase inventories by the obtained production every 12 simulated time steps.

A visual representation of the basic functioning of the dynamics is given in Figure 4.

Figure 4: diagrammatic representation of the primary events of the dynamics implemented by the software.

The figure displays the dynamic of a system organized as in Figure 1. Furthermore, here we envisage an agriculture system where the three producers harvest once a year. After the initialization, the software enters the main loop. Because each producer harvests once in the loop, an iteration corresponds to a year. From this figure, we understand that each market opens every two months (six times in a year), and therefore a loop is made up of six simulation steps. As specified above, the order of market openings is related to the working hours of the market place; therefore, looking at this figure we can understand that market 2 is located in a more westerly place than market 1. We deduce from Figure 3 that market 1 is in Sydney and market 2 in Brussels. We took as an example an agriculture commodity, because the plants' growing period, and therefore harvesting time, can depend on the latitude of production places. Hence, Figure 3 also shows the three producers at different latitudes.

It is useful to highlight that Figure 4 does not report all the events in the main loop. The complete sequence of events is given in the following list, which integrates and organizes the elements given above:

1. producer countries decide to allow or forbid exports and imports
2. buyers update buying strategy
3. market sessions are performed:
    - market 1
        - session 1
            - producer sends supply curve
            - buyers send demand curves
            - demand curves are aggregated
            - market price and quantities are determined
            - buyers increase inventories by the quantity bought in this session
            - producer decrease inventories by the quantity sold in this session
        - all the other sessions (if they exist) perform the same actions listed for session 1

- all other markets (if they exist), perform the same actions listed for market 1

4. buyers decrease inventories by the consumed quantity
5. producers produce

We point the interested reader to the software manual for a detailed description of these phases.

Illustrative Example

Among several possibilities that can be obtained by changing the initial settings, we report in this section the results of a simulation which implements the system described in Figures 1, 3 and 4.

As already mentioned above, in the setting we are examining, there is one producer and one buyer in each of the following countries: Argentina, Burundi and China. Two additional countries, Djibuti and Ecuador, have a buyer, but not a producer. There are two markets for bargaining the commodity: Sydney and Brussels. Following Figure 1, Argentina and China (countries A and C) sell in Sydney (market 1), while Burundi (country B) sells in Brussels (market 2). In contrast to Figure 1, we consider a situation with no commercial restrictions. This means that all the buyers, including China, can also buy from Argentina and Burundi, and China can also sell to all the buyers. Another difference concerns Figure 4. In this section, we set up the model in such a way that markets open once a month instead of every two months. The commodity is harvested once a year, and the gathering month depends on the country's latitude. It is assumed that Argentina obtains the product in August, Burundi In June and China in February. The quantity obtained by each producer at production time is given by its normal level of production, plus a random shock. Furthermore, to keep the model simple we give producers a trivial selling strategy: the quantity offered in each market session is the harvested quantity divided by 12, i.e. each month the constant quantity that would use up the harvested quantity is offered in the market.

Figures 5-8 show the dynamics of the system over 10 years. Various aspects of each agent are monitored. Each market session records the price agreed by buyers and the seller, as well as the quantity exchanged. Prices in each market session are reported in Figure 5, while Figure 6 focuses on the Chinese session, also reporting the volume of transactions (similar charts can be made for the other sessions, but we do not include them in this paper to save in space).

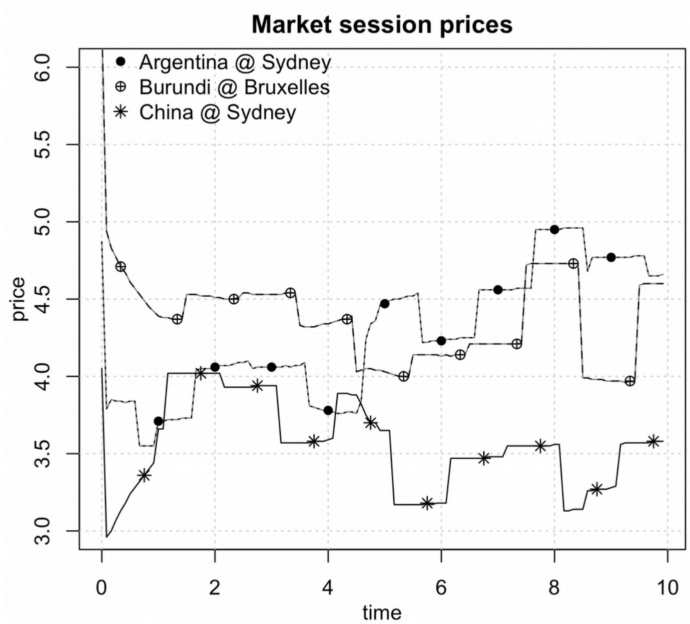

Figure 5: monthly prices of the three market sessions of the model.

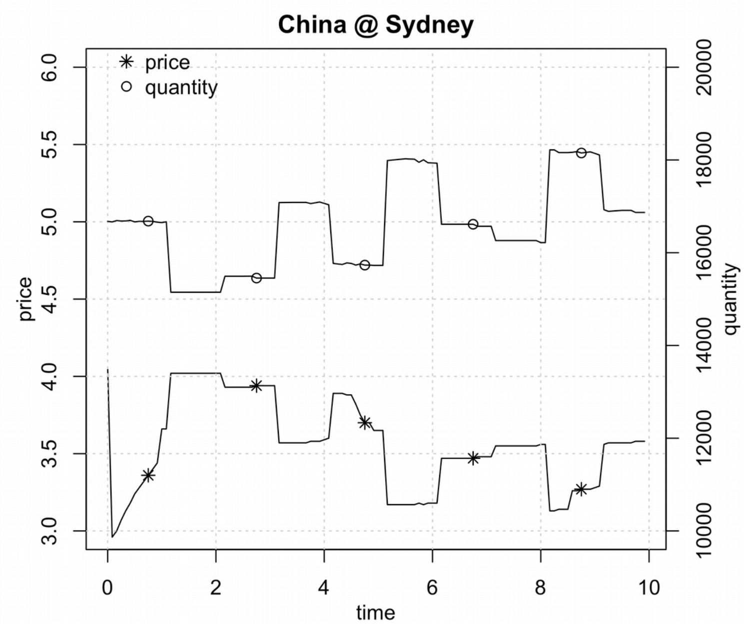

Figure 6: monthly price and quantity exchanged in the Chinese market session.

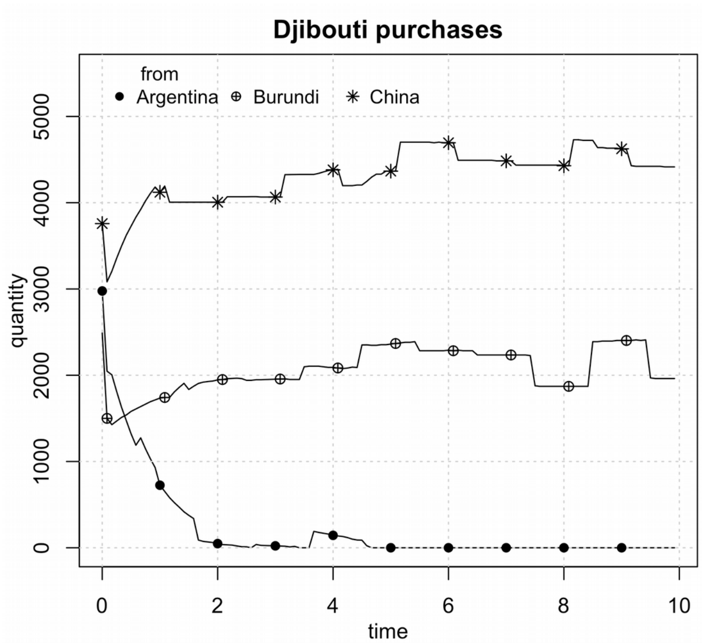

Figure 7: origin of Djibouti purchases.

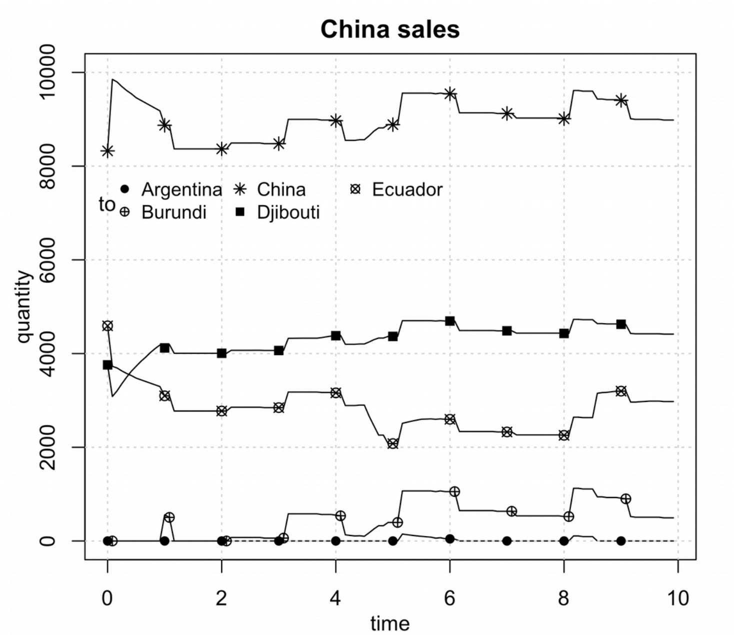

Figure 8: destination of Chinese sales

Each buyer records the vector of prices payed and that of quantities obtained in each market session. Figure 7 provides an example showing the sources of Djibouti's provision.

Each producer records the price and the quantities sold to each buyer. Figure 8 provides another example showing the destination of Chinese sales.

In addition to all these variables, it is possible to map the network of commercial exchanges in a given time and to monitor its evolution in time. Figures 9 and 10 show the network of exchanges among countries in month 50 and 100, respectively.

Figure 9: map of commercial relationships in simulation time step 50.

Figure 10: map of commercial relationships in simulation time step 100.

The convention that commodity flows clockwise is used to set the edge's curvature in the figure, while the edge's thickness is proportional to the quantity moved. Consider, for example, the edge linking Argentina and Ecuador: Moving from Argentina toward Ecuador implies the clockwise direction, therefore Argentina is the exporter and Ecuador is the importer. Following these conventions, it is possible to see, for example, that at time step 50, China exports to all the other countries, while Djibouti imports from China and Burundi. The comparison between Figures 9 and 10 confirms the most important commercial relationships, but also shows that the network changes in time: The China-Argentina relationship is active at time 50 but not at 100.

The example given in this section illustrates how the software helps in gaining a detailed knowledge of the dynamic system at hand. Once a commodity is chosen and a more realistic framework is investigated, the model can be used to evaluate the effects of significant changes of the economic context, such as relevant production shocks, import and export bans, and changes in government policy, among other factors.

Conclusions and future research directions

This paper reports the first step of a research project aiming to perform a study of commodity markets using agent-based computational techniques. There are many aspects to be considered when modeling a commodity market and designing a model able to account fro the features of all the commodities is not possible. However, many commodities are exchanged in international wholesale markets. The present work aims to provide a tool to model these exchanges, thus representing a starting point for the analysis of different commodities. There are many elements to be better qualified and specified in the present version of the model, and others will be introduced to reach a realistic model of a chosen commodity or group of commodities.

Modeling demand and supply is perhaps the first effort to be made by the researcher in adapting the software to the commodity s/he is interested in. In the current version of the software, the supply for each producer is a random variable whose mean and variance can be set in the producer's configuration file. Buyers' demand curves in each market session are linear, and their initial intercepts and slopes are also taken from the configuration file. A slightly more sophisticated modeling was possible for the demand curves dynamics: Buyers are allowed to gradually move demand from expensive to cheap market sessions (see the software documentation for details). However, implementing details in both supply and demand is a key step to be taken in the model development strategy. Such modeling will depend crucially on the time horizon of the analysis. In the long run, other factors affect supply and demand of several commodities and therefore should be included in the model. Examples of these factors include climate change, economic development, the appearance of new technologies and the dynamics of the population.

Government policies and business cycles are among the drivers in the medium term. The short run can be also affected by financial investments in commodities markets. The inclusion of new agents such as fundamentalists and chartists operating in commodity markets would also be a potential future integration of the model.

Another possible worthy integration is to allow for product differentiation. This aspect also concerns the demand side of the model. In the present version of the software, products differ because they are stored in different places, but their quality is homogeneous. A possible future direction of research is to allow for heterogeneous goods, which are imperfect substitutes. The concept of Armington Elasticity (Armington, 1969) provides a possibility of enhancing the model using traditional microfoundation. However, the approach taken in this work allows for considering other microfoundation strategies, based on behavioral, cognitive or heuristic principles.

We conclude by saying that agent-based computational techniques have the flexibility to account for all the peculiar aspects of the various commodities and, moreover, to use traditional or novel microfoundation to model agent behaviors. Progressing this research project requires an extraordinary amount of work that could be better performed in cooperation with other researchers. The source code and the detailed documentation provided seek to lower the effort of those who will find this work a good starting point for investigating the aspects they are interested in.

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