# From market to non-market: an autonomous agent approach to central planning.

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# From market to non-market: An autonomous agent approach to central planning[1]

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**Abstract**

In the longstanding debate in political economy about the feasibility of socialism, the Austrian School of Economists have argued that markets are an indispensable means of evaluating goods, hence a prerequisite for productive efficiency. Socialist models for non-market economic calculation have been strongly influenced by the equilibrium model of neoclassical economics. The Austrians contend that these models overlook the essence of the calculation problem by assuming the availability of knowledge that can be acquired only through the market process itself. But the debate in political economy has not yet considered the recent emergence of agent-based systems and their applications to resource allocation problems. Agent-based simulations of market exchange offer a promising approach to fulfilling the dynamic functions of knowledge encapsulation and discovery that the Austrians show to be performed by markets. Further research is needed in order to develop an agent-based approach to the calculation problem, as it is formulated by the Austrians. Given that the macro-level objectives of agent-based systems can be easily engineered, they could even become a desirable alternative to the real markets that the Austrians favour.

## 1 Introduction

The question of whether economic coordination and efficiency can be achieved in the absence of the market is one that has been a matter of longstanding debate in political and economic theory. It has preoccupied both academics, during what is now known as the 'socialist calculation debate', and practitioners during the attempts at central planning during the twentieth century in countries such as the Soviet Union. A number of different methods have been devised for calculating 'shadow prices' to serve as a substitute for prices that emerge from the process of market exchange. The various proposals for non-market planning have been the subject of strong criticism from the Austrian school of economists, most notably Ludwig von Mises and Friedrich A. Hayek. They argue that the proposed models for calculating shadow prices overlook the essential problem of socialist calculation. Since the 1980s, the Austrian position has been the subject of renewed interest (see, for example, Vaughn, 1980; Murrell, 1983; Lavoie, 1985; Ramsay-Steele, 1992; Boettke, 1993). Their work helps to explain some of the problems that plagued attempts at central planning during the twentieth century such as in the Soviet Union and Eastern Europe (Boettke, 1993). Such attempts to completely replace the market with planning are now widely viewed as doomed to inevitable failure. In the absence of a satisfactory response from the left to this 'calculation problem', the Austrian case for markets would seem to have been vindicated.

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It is argued here that 'multi-agent systems' (MASs) offer promise as a possible new approach to the challenge of calculating shadow prices. The founding principles of MAS parallel the understanding of markets in the Austrian School of Economics, and this suggests that it might offer some answers to the 'socialist calculation problem' as the Austrians presented it.

This paper shall firstly introduce the problem of economic calculation. Some of the key proposals for the non-market calculation of shadow prices are then summarised and the Austrian critique of them explained. There follows a brief review of recent research applying MASs approaches to the simulation of markets, work that has particular relevance for addressing problems of economic calculation. Finally, some key features of a potential application of MAS to the socialist calculation problem are outlined. The suggestions offered here are intended to prompt further discussion and possibly the implementation of this potential application.

## 2 Introducing the calculation problem

The question of why we need markets was a central focus for a group of Austrian economists whose work is of defining importance for the modern-day case for markets. Of particular significance is the work of Ludwig von Mises, who argues that market exchange is a necessary condition of rational economy (Mises, 1935).[2] Mises points out that markets generate prices which allow economic actors to compare qualitatively different goods, the value of which would otherwise be incommensurable. In the absence of markets and money as a commensurable unit of valuation, economic actors would be unable to make rational decisions concerning productive alternatives.

Mises' argument is developed in response to the proposals of some socialists who sought to establish a non-market system of planning.[3] His critique draws a distinction between the spheres of production and distribution under socialism. He points out that it is possible for markets to be confined to the sphere of distribution, while production is organised on the basis of non-market planning.[4] It is non-market planning in the sphere of production that is the defining feature of socialism. This means the removal of markets for factors of production, i.e. the natural resources, human labour and manufactured goods, which are used in the production process. Mises contends that the essential problem for socialism is that of how to evaluate the factors of production in the absence of the factor prices generated by such markets. He stresses that the problem arises even when a set of output targets have already been established by a political decision. Prices serve as a commensurable unit in terms of which the value of different goods can be compared. In their absence, it would become impossible in all, but the very simplest, economies[5] for producers to evaluate the 'diverse' range of modern productive processes (ibid, p. 96), later referred to by Mises as the oppressive plenitude of economic potentialities'' (ibid, p. 101). This problem of how to evaluate factors in the absence of factor markets is now known as the 'economic calculation problem' for socialism, or the 'socialist calculation problem' (Armentano, 1969, p. 129; Lavoie, 1985, pp. 51–54; Boettke, 1990, p. 13). For Mises and then later for Hayek, the problem is insoluble.

The calculation problem is not the only argument against non-market socialism put by the Austrians. Hayek, in particular, emphasises the political difficulties that would be involved in establishing the production objectives that Mises' formulation of the calculation argument assumes as given. A further problem is whether adequate incentives for producers would exist in the absence of the monetary incentives created by markets. However, the Austrians make clear

[2] A little known, early version of the argument had been offered by Pierson in 1902 and versions by Weber and Brutzkus were published contemporaneously to Mises. Yet Mises' paper is generally agreed to be the most comprehensive statement of the 'economic calculation argument' against socialism (Lavoie, 1985, p. 2n).

[3] His argument is particularly directed towards the socialist Otto Neurath.

[4] He goes on to argue that the emergence of such a consumer goods markets would be inevitable in an economy that started out as entirely non-market (Mises, 1935, pp. 91–93).

[5] The examples of such a simple economy discussed by Mises are that of the ''farmer in isolation'' and a one-man, 'Robinson Crusoe' economy (Mises, 1935, p. 96).

that they consider the calculation problem alone to constitute a decisive argument against non-market socialism. As Mises puts it, even granting the ‘utopian’ assumption that “each individual will exert himself with the same zeal” as in the market economy of today, “there still remains the problem of measuring the result of economic activity in a socialist commonwealth which does not permit of any economic calculation” (Mises, 1920, p. 120). Hayek was later to further emphasise Q1
how, in the absence of the information encapsulated by market prices, even the best intentioned socialist planners could not achieve economic efficiency. The calculation problem therefore underpins the Austrian thesis and requires thorough assessment before their further arguments are considered.

## 3 Three models of socialist calculation

Various attempts to address the calculation problem have emerged, in both theory and practice from socialist-inspired economists. These are considered below. Firstly, there is consideration of the theoretical model of socialist calculation developed in response to Mises in the 1930s and based upon the general equilibrium model of neoclassical economics. Two specific computational techniques are then discussed, those of input–output analysis and linear programming, both of which were adopted by Soviet planners.

### *3.1 The neoclassical model*

A model of socialist calculation based upon neoclassical assumptions was developed by socialists in the 1930s, such as Oskar Lange and Henry Dickinson. Their work drew from the mathematical model of socialist pricing outlined by Enrico Barone in his 1908 paper entitled ‘The Ministry of Production in the Collectivist State’.

Barone’s model was based upon the following three assumptions.

1. the quantities of fixed capital are known;
2. the production functions (or ‘productive co-efficients’) for producing goods are known;
3. the level of social welfare produced by any given level of production is known.

From these assumptions, Barone demonstrated that it is possible, in principle, for a socialist ministry of production to establish a set of ‘prices’ (or ‘equivalences’ as he refers to them) that are analogous to market equilibrium. As Schumpeter puts it:

> “The essential result of Barone’s or any similar investigation is that there exists for any centrally controlled socialism a system of equations that possess a uniquely determined set of solutions, in the same sense and with the same qualifications as does perfectly competitive capitalism, and that this set enjoys similar maximum properties. (Schumpeter, 1954, p. 988)

Henry Dickinson proposed that the mathematical model defined by Barone could be used by the central planning board (C.P.B.) to calculate prices for the factors of production and consumer goods (Dickinson, 1933). For Oskar Lange, another socialist, the significance of this neoclassical model was that it showed there to be no necessary connection between equilibrium prices and market
Q2 exchange (Lange, 1937, p. 54). Unlike Dickinson, Lange dismissed the need for centralised, non-market price fixing to be based upon the solution of ‘hundreds of thousands of equations’ (ibid, p. 67). Instead, he suggests that, through a process of trial and error adjustment, the C.P.B. could ensure that equilibrium is reached. This procedure would involve raising the prices for those factors of production that fall short and lowered for those that accumulate (ibid, p. 66).

In spite of the mathematical soundness of the neoclassical model, it is questionable whether Barone himself saw equation-solving to be a practicable procedure for central planning (Lavoie, 1985, p. 21), and it is far from clear that he intended his model to serve as the basis for a feasible method of non-market pricing. Barone’s paper, whilst not explicitly stating whether his model could be applied in practice, does comment dryly on the bureaucracy required by socialism, referring to the "army of officials whose services would be devoted not to production but to the laborious and colossal centralization work of the Ministry" (Barone, 1935, p. 290). Here, Barone is alluding to the vast amount of data that would need to be centralised in order for the ministry to calculate the prices using his model.

The Austrian Schools, especially Hayek, were highly critical of such a mathematical model of socialist pricing. According to the Austrian critique, which was directed towards neoclassical economics in general, it was based upon flawed assumptions (Hayek, 1949, p. 188). Hayek contends that the knowledge assumed by the neoclassical model to be known can be discovered only through the market process of competition and innovation. He writes of competition as being "a procedure for the discovery of such facts as, without resort to it, would not be known to anyone, or at least would not be utilised" (Hayek, 1978, p. 179). Hence, he scathingly refers to the second assumption of the neoclassical model as being that the production costs, or 'cost curves', of producers "are an objectively given fact ascertainable by inspection, and not something which can be determined only on the basis of knowledge and judgment—a knowledge which will be wholly different when he acts in a highly competitive market from what it would be if he were the sole producer or one of a very few" (Hayek, 1979, p. 69). Hayek's treatment of the third assumption concerning the knowledge of consumer preferences is similarly critical (Hayek, 1949, p. 38).

Strictly speaking, the third assumption, that consumer demand schedules are known, need not be included in a mathematical model designed to answer Mises' calculation argument. As explained in Section 2, this argument assumes that target outputs have been fixed. Still, from the Austrian perspective, the second assumption, in particular concerning knowledge of production methods, represents a fatal weakness of those proposed solutions that are derived from the neoclassical model. The different quantitative techniques that economists sought to apply to problems of non-market production planning have tended to be vulnerable to this Austrian critique. Two of the most notable planning techniques that were used by Soviet economists, input–output analysis and linear programming, each adopt the first two of the Barone assumptions that the productive coefficients and the quantities of fixed capital are known. They drop the need for the third assumption about the social welfare function by assuming that a target set of output goods has been defined.

### *3.2 Input–output analysis*

The technique of input–output analysis was developed by the economist, Wassily Leontief (1966). It was originally designed as a tool for the analysis of the interrelationships between different sectors of an economy. Yet, the method prompted considerable interest from Soviet economists who were concerned with the problem of designing non-market production plans. Leontief's 'matrix inversion' procedure for calculating the aggregate output of all goods (including factors of production) required to meet a given net output target assumes a 'technology matrix' **A** of production coefficients. This is an $n$ x $n$ matrix where there are $n$ goods in the economy.

Leontief showed that

$$\boldsymbol{x} = (\mathrm{I{-}A})^{-1}\check{\boldsymbol{y}},$$

where $(\mathbf{I{-}A})^{-1}$ is the inverse of **A** (referred to as the Leontief inverse) and $\check{\boldsymbol{y}}$ is the $n \times 1$ vector of net output targets (Jacques, 1999, p. 449).

The matrix inversion procedure is a means of solving $n$ simultaneous equations, but is not, in itself, an answer to the problem that concerned the Austrians of how to achieve an efficient factor allocation. Achieving a plan balance in the sense that the target output $\check{\boldsymbol{y}}$ is produced does not necessarily mean that the gross output $\boldsymbol{x}$ is minimised. For a given balanced plan, it might still be possible to reduce the gross output of a good $j$ ($xj$) without increasing the gross output of other goods and so to still achieve the target output $\check{\boldsymbol{y}}$. Hence, the input–output and plan balancing methods outlined above do not, in themselves, offer a means of optimising the allocation of inputs in the face of resource constraints (Cockshott and Cottrell, 1993, pp. 92–94).

### *3.3 Linear programming*

The problem of achieving an optimal factor allocation was the challenge addressed by the Soviet economist, Leonid Kantorovich, who formulated the technique of linear programming for optimising an objective function subject to constraints. Amongst the multitude of optimization problems to which the technique can be applied is, as Kantorovich shows, the problem of minimising the inputs required to produce a target output.

The computational cost of linear programming means that it faces a problem of scalability when applied to problems where the production of millions of products needs to be planned (Cockshott and Cottrell, 1993, p. 88). Cockshott has devised a 'plan-balancing algorithm' that he considers to be more suitable for addressing this kind of large-scale optimization problem. The model is based upon the use of a neural network, designed to represent the economy. It is assumed that the productive coefficients for each industrial sector are known (Cockshott, 1990, p. 434). Each cell on the network represents an industry and is "set up with appropriate weights on its synapses to represents the strength of its coupling to other industries" (ibid, p. 435). The total output of the simulated economy can be calculated from this combination of coefficients and weights. In an iterative process of training the network, the weights are adjusted using a simulated annealing algorithm to reduce the distance from the target output. Cockshott shows that such a network reaches a solution that "was correct to within rounding errors", and that "the run times are approximately a linear function of the number of industries" (ibid, p. 441).

The neoclassical approach of defining a set of simultaneous equations for calculating factor values is an example of the equation-based approach to systems design. The neural network developed by Cockshott is a more robust and scalable model for achieving a large-scale matrix inversion. It also offers the potential of being able to accommodate non-linear production functions, a possibility that Cockshott does not explicitly consider, as his experiments assume linear production functions (Cockshott, 1990, p. 436). However, this model, just like input–output analysis and linear programming, assumes a set of productive coefficients as given. None of the four approaches discussed here search the space of alternative technologies. As Hayek points out, such a process of 'knowledge discovery' is a core function of markets.

## 4 Autonomous agents and virtual markets

MAS has been shown to offer some significant advantages over the equation-based approach in a range of disciplines and applications, ranging from biological simulations to the development of computer simulations in the social sciences (Gilbert and Troitzasch, 2005). System-level behaviour, rather than being defined in advance by equations, emerges from the interactions of agents. MAS has an advantage over other types of complex, adaptive system in terms of the depth of information that the agents can store and the variety of functionality they can embody. As Endriss and Maudet remark, the use of MAS models can be thought of as reaching a 'solution' to a particular 'problem' that the society generates (Endriss and Maudet, 2004, p. 93). These are often problems that involve 'resource allocation', in some sense. For example, some notable applications where successful implementation has been achieved in industry address problems in operations research, such as task allocation and scheduling. MAS has been used by the consultancy firm, EuroBios, to assist logistics analysts and plant schedulers at Air Liquide. This firm has also successfully introduced similar technology to Southwest Airlines in the USA (Luck *et al.*, 2003, p. 30). British Telecom uses MAS to allocate resources in response to customer requests for services (e.g. Virginas *et al.*, 2003).

The problems addressed by MAS are often analogous to those studied in economics, a discipline that defines itself as the study of the allocation of scarce resources (Samuelson and Nordhaus, 1995, p. 6). The potential applications of MAS in economics are gaining increasing attention. MAS approaches have been used for simulating economies in order to gain insight into real-world economies and assessing the impact of policies. For example, there has been a significant amount of work in developing the MAS simulations of electricity markets. This sector has been the focus of strong interest in the light of recent restructuring and deregulation. MAS can be used to provide insight into the effects of different market designs upon economic behaviour. For example, Nicolaisen *et al.* (2001, p. 2) construct "an agent-based computational model of a wholesale electricity market that can be used as a laboratory for systematic experimentation".

Another way in which economics can connect with MAS is that, as Cliff and Bruten (1998, p. 2) put it, the market can be used as "a metaphor for constructing computational solutions to difficult problems". Cliff and Bruten refer to this area of research as 'market-based control' (MBC), in which "groups of software agents or 'traders' interact within a market-like framework" (ibid, p. 2). An MBC system assigns responsibility for the sale and purchase of resources to agents that are situated within the environment. Each agent has responsibility for a particular set of demands or supply of resources of which they have exclusive knowledge. Agents initiate exchanges of resources where such exchanges are of mutual benefit to the participants through a pre-designed exchange protocol.

A core question for the design of MBC systems is that raised by the economist Vernon Smith on the relative importance of market structure, as opposed to the capabilities of economic agents in the equilibration process in market economies. Smith's research analysed different market structures including auction mechanisms and a retail model. Auction mechanisms, differing in terms of their rules for establishing the outcome of bids and the resultant clearing price, were shown by Smith to vary in the speed at which they reach equilibrium. Smith and others have shown that the 'continuous double auction' (CDA), which has been used in various stock exchanges around the world including the New York Stock Exchange, is the 'fastest and most efficient market structure' (Cliff and Bruten, 1998, p. 3). In the CDA, buyers and sellers quote, or 'shout' a bid/offer price at any point in time. Sellers and buyers can then choose whether to accept or reject it. Both sellers and buyers have a 'limit price'. For sellers this is a minimum price they are willing to accept, and for buyers it is the maximum price they are willing to pay. The series of buyer and seller limit prices constitute the demand and supply curves for the product(s) being traded.

Smith's research involved human traders in a series of experiments in which participants would be either a buyer or a seller. Each seller was given a commodity to sell and each buyer was given the right to buy certain commodities, along with some currency. Agents are assigned limit prices that are private knowledge to them. These limit prices of sellers and buyers constitute the supply and demand curves, respectively, in the experimental economy (ibid, p. 2). Smith's results showed that as few as 20 traders could converge upon the theoretical equilibrium price.

Smith's highlighting of the potential for equilibration in such a small market prompted further interest in the question of the extent to which this equilibration is due to market structure or the intelligence of traders. The work of Gode and Sunder investigated this question by testing a simulated market in which computer agents have zero intelligence.[6] Their zero intelligence (ZI) traders submit bids that are random within a certain budget constraint. Their conclusion that ZI traders can reach equilibrium has since been shown to be incorrect by Cliff and Bruten (1997). Gode and Sunder were, therefore, wrong to conclude that "the imposition of the budget constraint (upon traders), is sufficient", when combined with a certain market structure, to reach equilibrium (Cliff and Bruten, 1997, p. 2). Hence, while the question of auction design has been shown to be ripe for further research (Phelps *et al.*, 2002), the question of how to define the bargaining capabilities of agents is also of key importance for the effectiveness of MBC systems in reaching equilibrium.

Some early MBC models relied upon a centralised decision on to whether accept or reject bids, which was made using a centralised model of the network (Cliff and Bruten, 1998).[7] Hence, these models did not address the task of designing agents with the strategies for setting bids and offers. In addressing this challenge, Cliff and Bruten offer their own ZIP ('zero-intelligence plus') traders that submit bids stochastically whilst also employing an elementary algorithm that enables them to learn from experience. ZIP agents of both types seek to maximise their profit, defined for

[6] A detailed review of their work is provided in Cliff and Bruten (1997).
[7] The collection to which they refer is Clearwater, ed, 1996.

both buyer and seller agents as the difference between the transaction price and the agent's limit price. ZIP traders are shown to "stabilise at an equilibrium that is predictable from economic theory, and are robust with respect to sudden changes in the market" (Cliff and Bruten, 1998, p. 1). A 'proof of concept' application of ZIP traders to the problem of resource allocation on a large computer farm has since been developed by Robinson (2002). Progress has also been made in the design of alternative algorithms to ZIP. The Roth–Erev reinforcement-learning algorithm is an alternative that is used by Nicolaisen *et al.* (2001) and Phelps *et al.* (2002). Tesauro and Das (2001) have found that their modified version of the 'GD algorithm' developed by Gjerstad and Dickhaut (1998) outperforms ZIP.

This progress in the development of bidding algorithms now means that software bidding agents are able to consistently outperform human bidders. In a summary of his research findings on this question, Jeff Kephart writes: "The agents' superior performance suggests they will be used on a broad scale, which in turn suggests that interactions among agents will become frequent and significant" (Kephart, 2002, p. 7207). Hence his view that: "Humans are on the verge of losing their status as the sole economic species on the planet" (ibid). As evidence that this trend is already well under way, Kephart points to the growing use of computational agents in automated auction markets on the Internet. He expects them to have an especially significant role in what he refers to as the 'information economy':

> "Many economic software agents will function as miniature businesses, purchasing information inputs from other agents, combining and refining them into information goods and services, and selling them to humans or other agents. Their mutual interactions will form the *information economy*: a complex economic web of information goods and services that will adapt to the ever changing needs of people and agents. The information economy will be the largest multiagent system ever conceived and an integral part of the world's economy". (ibid)

The potential scalability of MAS is highlighted by Kephart when he states that "The information economy will be by far the largest multiagent system ever envisioned, with numbers of agents running into the billions" (ibid, p. 7212).

Indeed, it is a feature of such market-based systems that the larger the number of participants, the smoother the process of equilibration, and it is the systems with a very small number of participants that present the greatest challenge for resource allocation theory.

## 5 The Austrian case for autonomous agents

There are some strong parallels between the case for an agent-based approach to computation and the Austrian case for markets. This is evident if we assess the Austrian view of markets against the six rules of thumb that have been formulated by Peter McBurney to assist in the decisions about whether an agent-based approach is appropriate for a given domain. The six rules are as follows:

"1. Are there multiple entities in the domain, or can the domain be represented as if there are?
2. Do the entities have access to potentially different information sources or do they have potentially different beliefs? For example, differences may be due to geographic, temporal, legal, resource or conceptual constraints on the information available to the entities?
3. Do the entities have potentially different goals or objectives? This will typically be the case if the entities are owned or instructed by different people or organizations?
4. Do the entities have potentially different preferences (or utilities) over their goals or objectives?
5. Are the relationships between the entities likely to change over time?
6. Does a system representing the domain have multiple threads of control?" (McBurney, 2005).

McBurney suggests, "If the answer is YES to Question 1 and also YES to any other question, then an agent-based approach is appropriate" (ibid). For a market domain, the answer to all of McBurney's questions would be 'yes.' As we have seen, the Austrian account of markets particularly emphasises some of the domain characteristics that McBurney identifies, including the dispersal of information, the variety of goals and the inevitability of change that characterise economies. The justifications for agent-based systems in general and market-based MAS models in particular are often reminiscent of the Austrian case for markets. For example, Tesfatsion notes that "(o)ne key departure of agent-based computational economics (ACE) modelling from more standard approaches Q3 is that events are driven solely by agent to agent interactions once initial conditions have been specified. Thus, rather than focusing on the equilibrium states of a system, the idea is to watch and see if some form of equilibrium develops over time" (Tesfatsion, 2006, p. 843). Such a focus upon the process through which economies tend towards equilibrium, rather than upon the mathematical definition of the equilibrium state itself, is a hallmark of the Austrian approach.

The point that market domains are so conducive to agent-based approaches raises the question of whether MAS might be applied to the problem of socialist calculation. The scalability of MAS is of potential importance here, given the scale of the economic calculation problem in a modern economy, as highlighted by the Austrians. Furthermore, agents can incorporate non-linear utility functions more easily than simultaneous equation-based approaches, a significant point given that production functions are often non-linear.

This potential new approach to the long-running problem of calculating shadow prices has yet to be recognised in the literature on either the socialist calculation debate or MASs. However, just as the MAS literature has identified the importance of markets as a possible domain for MAS, the literature on Austrian economics has noted parallels between MAS and Austrian economics. In an early paper on the topic of market-based systems of computation, Miller and Drexler quote Hayek on the importance of principles such as prices encapsulating information and spontaneous order emerging from decentralised decisions (Miller and Drexler, 1988b, pp. 138–140). This parallel between the Austrian account of the market process and the design principles of MBC systems has since been observed by Lavoie (Lavoie, 1990, p. 76). However, Lavoie overstates the implications of what he takes to be Miller and Drexler's conclusion that "whatever degree of intelligence computers have, it is best used not by substituting for, but by integrating with, human markets" (ibid). While, of course, it is important for the objectives of MAS to be established through a process of human decision-making, the question remains of where this boundary should be. The emphasis of Miller and Drexler is that MBC systems could be designed to solve large, complex coordination problems with the only human intervention required being that of designing a framework (or 'domain') which is conducive for agents to reach a solution. Rather than ruling out the possibility of applying MAS to the problem of calculating factor values, the early literature on MAS needs to be viewed as prompting economists and MAS researchers to address this very question. Sections 6 and 7 below raise some key themes that need to be addressed by such an investigation.

## 6 A framework for virtual factor markets

In view of the discussion above, some of the key features of an MAS system for addressing the socialist calculation problem can now be suggested. This system, of which only an initial sketch is provided here, is to be referred to as a virtual factor market (VFM). It is beyond the scope of this paper to provide a definitive model, and hence the precise algorithms that would be required are not specified. Also, the model presupposes that certain decisions are made by the processes external to VFM. Questions concerning the form of these separate procedures, including the question of whether they could also be addressed by MAS systems, are not considered here.

In VFM, buyer and seller agents represent production units, trading factors of production that they require in order to meet output targets. As in Mises' formulation of the calculation problem, output targets are assumed to have been pre-specified. The buyer agent for each production unit is centrally assigned a certain amount of currency in order to purchase the factors of production that it requires to meet its targets. Production units possess a certain quantity of capital, and an associated space of possible production functions is known to their buyer agent. Buyer agents calculate the most cost-effective production function for their production unit on the basis of (i) their local knowledge of the production possibility space and (ii) their knowledge of current prices. From these two sets of information, a demand function for the required factors can be inferred. Agents engage in an iterative process of bidding for factors, adjusting their demand functions where necessary in response to changing prices.

The advantage of this approach, when compared to the alternative methods, is that it enables agents to store and utilise locally held knowledge. The MAS methodology allows for agents to be designed to either store or have easy access to local information without the need for it to be communicated to a central planning agency. As discussed above, numerous market-based MAS models have been developed, which are decentralised in the sense that individual agents are responsible for accepting bids and offers. It is important to note, however, that these models still involve the demand and supply functions of agents in the form of limit prices being pre-specified by the modeller.[8] This was true of the Santa Fe auction tournament (Rust *et al.*, 1993), the experiments of Cliff and Bruten and more recently the simulations of Tesauro and Das (2001). The same is true of the key studies of electricity markets by Nicolaisen *et al.* (2001) and Bagnall *et al.* (2005). Tesfatsion's Q4 *ACE Trading World* also pre-specifies the cost curves of producers and the utility functions of consumers (Tesfatsion, 2006). In order for VFM to provide a solution to the calculation problem as presented by the Austrians, agents would be required to dynamically generate their own supply and demand curves on the basis of their production functions and target outputs alone. This kind of adaptation would seem to be well within the scope of the MAS approach, but the question of how it is to be achieved in market simulations is one of the key challenges facing VFM. The computational procedure by which agents use their local knowledge of production possibilities to search the space of possible demand functions is left unspecified here. The virtue of the MAS methodology is that it allows scope for investigating different methods by which the agents might perform such a task.

A further significant challenge for VFM is that of how to distribute the purchasing power between buyer agents in order to reflect the macro-level priority of different output targets. When purchasing power is first assigned, factor costs are not known and so there is a need for assignments of purchasing power to be subsequently adjusted in the light of changing prices. VFM might, therefore, involve a dual process of equilibration, as factor prices and purchasing power assignments adapt simultaneously. How to engineer such a dual process would seem to be another significant challenge in the development of VFM.

## 7 The advantages of virtual markets

The discussion in Sections 4, 5 and 6 above suggests that VFM could simulate the dynamic, knowledge discovery functions of the market process highlighted by the Austrian school. Yet, VFM also offers the opportunity for efficiency gains in comparison to the market. This is because, as has previously been noted, MBC systems do have the potential advantage over real markets that the goals and constraints faced by the agents can be pre-specified by the designer of the model. Just as it is possible to design agents with a number of different welfare functions that are not necessarily based on individual self-interest (Endriss and Maudet, 2004), so it is possible to design macro-level welfare objectives for MAS societies that involve more than just the maximization of individual agents' self-interest. Two normative principles that the economists have sought to incorporate into social welfare functions are equality and environmental sustainability, each of which is excluded from the concept of market equilibrium.

Turning to the first of these two normative principles, the standard definition of market efficiency, known as Pareto optimality, excludes considerations of equity. Pareto optimality is defined

[8] An exception is the work by Robinson (2002) whose ZIP trader application for allocating network resources defines demand in terms of demand for network resources and the supply in terms of server space, variables that are subject to continual change (Robinson, 2002, pp. 55–56).

as a pattern of resource allocation in which no further mutually beneficial exchange of goods is possible. In other words, where it is impossible to make an individual better off without making somebody else worse off. As Michael Common puts it, Pareto optimality makes "no reference to how well off the individuals involved are" and it is "therefore consistent with massive inequality" (Common, 1995, p. 125).

Turning to the second normative principle, that of environmental sustainability, ecosystems are often public goods and the cost of unsustainable use is then excluded from market prices. Such environmental costs are defined as negative externalities, i.e. 'unintended effects' of the activity of firms or individuals that "do not figure in the costs and benefits associated with the activity of the firm or individual responsible for it" (Common, 1995, p. 128). Examples of externalities include negative environmental effects such as pollution and the unsustainable depletion of natural resources.

The potential for computational markets to overcome the failings of human markets such as externalities is noted by Miller and Drexler (1988a, p. 70). The welfare function of VFM could potentially incorporate the criteria of equity and sustainability. Externalities can be prevented in VFM by fixing the supply of ecological services at a sustainable level or by assigning a cost to negative environmental effects. Factor prices would then incorporate these costs or limits to supply.

As has been suggested, a MAS system can be designed to meet an equity condition through control of the relative purchasing power of the agents in the system. Of course, there are different possible definitions of equity. For example, the MAS devised by Lemaître and Verfaille (1999) for the allocation of a common property resource assigns purchasing power to agents according to their financial contribution to the establishment of the resource.[9] In VFM, a principle of equity could be reflected in decisions about output targets and the priorities level assigned to them.

## 8 Conclusion

The Austrian critique of the 'static', neoclassical models of central planning highlights some significant problems for the computational modelling of factor markets. Yet, agent-based approaches offer significant potential for addressing these challenges. Notable progress has been made in the design of algorithms for agent-based bargaining through a decentralised market process. Yet, the potential for modelling the dynamic interrelationships between production units in factor markets has not specifically been discussed. Recent contributions on Austrian economics make no mention of this possible approach to the socialist calculation problem. There are only a few references to the recent developments in adaptive systems in general, from which MAS emerged as a field of research. This is in spite of the strong parallels between the Austrian understanding of the market and the MAS approach to designing complex systems.

Of course, the task of creating virtual markets that can inform us about the real, human economy is a highly challenging one. Yet, the field of artificial intelligence has never been short of ambitious objectives. Given the expectation of researchers such as Kephart that virtual trading agents are set to play an ever increasing role in real economies, the aim of designing virtual markets that can be engineered to meet social objectives is certainly ripe for further investigation.

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[9] The common property resource in this application is a satellite and the MAS are used to allocate satellite resource by prioritising requests for photographs.

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