Modeling of Complex Economic Systems with Agent Nets

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Abstract

We consider a methodology for modeling, simulation and design of complex economic systems which we call *Agent Nets*. It is specifically designed to represent complex systems composed from independent entities called *agents* which transform and exchange information and other resources taking independent and coordinated decisions on the basis of incomplete information about state of the whole system and actions of other agents. Specifying particular cases of agents we can describe as Agent Nets distributed systems, which include mobile software agents as well as many different economic systems. In this paper we present mathematical description of Agent Nets, describe an Agent Net simulator MODAGENT created for simulation of multiagent systems and present a case study dealing with agent modeling of industrial relations in information industry which have implications for electronic commerce.

1 INTRODUCTION

Variety of distributed systems can be described as a collection of relatively independent units called here *agents* which process and exchange information, products, services, money and other resources, formulate and pursue strategies and make decentralized decisions directed towards achievement of aims. Taking as a reference telecommunications, we can see that in the case of the global area network such agents are the network nodes which exchange traffic flows and signaling and make routing and congestion control decisions. In the case of local ATM networks such agents are local exchanges with admission control units which negotiate resources with users and supervise the user behavior, while the users themselves can be considered another type of agents.

Another important example of multiagent system is presented by information industry understood as progressive intertwining of telecommunication industry, computer industry and content provision. As a result of deregulation and technological innovation this industry is composed from rich variety of enterprises which can combine different industry roles and engage in complex relations of competition and cooperation. In this case agents are enterprises and users of information products. More detailed analysis of information industry as multiagent system can be found in (Bonatti, Ermoliev and Gaivoronski 1998, Bonatti and Gaivoronski 1996, Bonatti *et al* 1996).

Historically the word *agent* was used extensively in economic modeling to describe economic subjects which make independent decisions. More recently the notion of "intelligent agents" was introduced to describe computer programs operating in distributed and networked reality like Internet and acting on behalf of a human taking intelligent decisions (Boman 97, Jennings *et al* 98). In our modeling of systems composed of agents we draw upon both of these notions.

In all of these cases there exist a number of successful approaches for modeling of individual agents. The modeling of systems of agents is, however, much more difficult task and became only recently a subject of active research. In this paper we consider an approach for modeling of multiagent systems which we call *Agent Nets*

Let us start by observing that although multiagent systems mentioned above are very different by nature, they possess the following common features, which suggest a development of common methodological approach for their modeling.

- *Network structure*. All these systems can be represented as graphs with agents being the vertices of the graph. The edges of the graph represent exchanges and interactions between agents. In the case of telecommunication network these edges correspond to the links between nodes, while in the case of information economy the edges are supplier-consumer relationships.

- *Transformation and exchange of resources and flows*. In all cases agents possess internal resources, transform input resources and flows in output resources and flows, and exchange traffic flows and resources. In case of the network nodes such internal resources are represented by processing capacities and buffers, the input flows are received packets and inbound connections, the output flows are outgoing packets and connections. In case of enterprizes internal resources are production capacities which transform input resources into products and services. In case of end users internal resources are terminals while input resources are connections, products and services. Agents exchange flows and resources. Examples of such exchanges include exchange of products for money, exchange of signaling between network nodes while establishing a connection, exchange of information for information. In what follows we consider as *resources* all ”passive” commodities transformed and exchanged by agents, including resources in common sense, but also all kinds of products, services, information and traffic flows.

- *Distributed asynchronous decision-making and control*. All agents take decisions, which involve assignment of input resources, treatment of input and output resources, selection of partners for exchange. These decisions are taken in independent and asynchronous way, although they can be coordinated. Examples of such decisions are routing, admission control and congestion control algorithms of telecommunication network nodes, production, development and marketing policies of enterprises, selection of service providers by end users. In selection of decision strategies agents seek to follow their individual criterions and aims which may or may not be coordinated with each other. Therefore the design of multiagent systems can not be reduced to simple global optimization criterions, like minimization of total costs or maximization of properly defined "public good".

- *Dynamics*. Multiagent systems can exhibit widely different dynamic behavior due to richness of positive and negative feedbacks usually present in such systems. They can have many equilibriums and switch in catastrophic manner between them. They can exhibit totally chaotic behavior even in the absence of random disturbances. Design based on the study of steady state behavior is not adequate because in many cases such systems change constantly. Examples of such nonstationary changes include rapid development of mobile networks and explosion of Internet.

- *Incomplete information and bounded rationality*. There are two main sources of uncertainty in multiagent systems: external and internal. External uncertainty is due to the fact that multiagent systems operate in uncertain and changing environment. Changing demand patterns and technological change are two examples of such uncertainty. Internal uncertainty appears because the agents have limited knowledge of strategies and states of other agents. Agents should employ decision principles, which take into account such uncertainty. However, even if the complete information would be available it is often impossible to use due to constraints on processing times. Therefore it is not realistic to consider agents as being completely rational maximizing some utility function. Instead decisions are made by *boundedly rational* agents on the basis of changing set of heuristics based on previous experience (Arthur, 1994).

In order to represent these features we consider a class of models called *Agent Nets*. It is a network like structure with agents being the vertices of oriented graph which edges define the exchanges between agents. This structure is associated with appropriate resource space with agents transforming and exchanging resources from this space. Each vertice of the graph is equipped with the set of transformation functions and strategies. The state of the vertice (agent) is defined by the vector of internal, input and output resources. There are dynamic relations which guide the evolution of the state of the agents similar to those considered in the theory of Discrete Event Dynamic Systems (Ho and Cao 1991, Gaivoronski *et al* 1992, Pflug 1992, Cassandras 1993, Rubinstein and Schapiro 1993).

We utilize the experience accumulated recently in other network models, in particular Petri Nets (Peterson 1981, Archetti, Gaivoronski and Sciomachen 1993), Neural Nets (Hertz et al 1991, Gaivoronski 1994) and Bayesian Nets (Neapolitan 1990, Archetti, Gaivoronski and Stella 1997). Petri Nets are very good in representing asynchronous distributed processes, however it is difficult to use them to represent nontrivial agents with resource transformation, exchange and control strategies. Neural Nets are useful models for recognition of complex patterns which can be present in multiagent systems, however they are lacking tools for representing distributed decision making. Bayesian Nets are good in processing incomplete information, but again lacking structure for agent representation. Therefore a new network model is needed for representing multiagent systems.

We should mention here related work in other fields, which partially addressed some of the issues treated here. Research in computational economy and market oriented programming resulted in creation of several tools for distributed resource allocation in financial and other fields (Even and Mishra 1996, Steiglitz et al 1995, Waldspurger et al 1992, Wellman 1993). Dynamic interactions between economic agents were considered in evolutionary economics (Dosi and Nelson 1993, Lane 1993).

In order to cope with uncertainties inherent in multi-agent systems we utilized approaches developed in stochastic programming (Birge and Wets 1987, Ermoliev and Wets 1988, Gaivoronski 1982, Higle and Sen 1991, Kall and Wallace 1994, Mulvey and Ruszczynski 1992).

The rest of the paper is organized as follows. In Section 2 we describe the notion of Agent Net and discuss some its properties. Simulation system MODAGENT developed for simulation of Agent Nets with application to modeling of information economy is presented in Section 3. Section 4 is dedicated to the case study from modeling of relations between network providers and providers of information services over telecommunication networks.

2 AGENT NETS

Agent Net is composed of two oriented coordinated graphs $\{(A,N),(R,P)\}$ where

(A,N) - the *agent graph* defined by the set of n_a vertices A called *agents* and the set of oriented arcs $N \subseteq A \times A$. Agents possess additional structure which will be defined separately. Arcs connect those agents which can be involved potentially in *transactions*.

(R,P) - the *resource graph* defined by the set of n_r vertices R called *resources* and the set of oriented arcs $P \subseteq R \times R$. Quantity and other attributes may be associated with each resource.

For each agent $a_i \in A$ let us define two sets: $A_i^+ = \{a_j | (a_j, a_i) \in N\}$ - the set of agents from which oriented arcs point to agent a_i;

$A_i^- = \{a_j | (a_i, a_j) \in N\}$ - the set of agents to which oriented arcs point from agent a_i;

Similarly for each resource $r_i \in R$ we define:

$R_i^+ = \{r_j | (r_j, r_i) \in P\}$ - the set of resources from which oriented arcs point to resource r_i;

$R_i^- = \{r_j | (r_i, r_j) \in P\}$ - the set of resources to which oriented arcs point from resource r_i;

The purpose of the Agent Net is to model transformation of resources from R by agents from A. Informally, R_i^+ is the set of resources which participate in transformation which result in resource r_i. In order to transform resources agents make transactions between each other. The set A_i^+ is composed from all agents which possess resources used in transformations performed by agent a_i.

2.1 STRUCTURE OF AGENTS

Agent Nets differ from other network like structures, notably Petri Nets, Neural nets and Bayesian Nets by more involved node structure which permits to model different types of agents found in real multiagent systems.

Agent a_i is a tuple $(T_i, I_i, O_i, E_i, S_i, F_i, M_i, D_i)$ where

$T_i \subseteq R$ - set of internal resources, these resources are needed to model production capacities and technical capabilities;

$I_i \subseteq R$ - set of input resources, these resources are obtained from agents belonging to A_i^+ in the process of transactions;

$O_i \subseteq R$ - set of output resources, these resources are obtained by transformation from input resources with the help of internal resources and constitute the *offer* of agent a_i to agents from A_i^-;

$E_i \subseteq R$ - set of exchange resources, these resources are exchanged by agent a_i with agents from A_i^+ for input resources.

These resource sets are connected with agent and resource graphs by the set of constraints, in particular

C1. For each $r_k \in I_i$ exists $a \in A_i^+$ such that $r_k \in O_j$.

C2. For each $a_j \in A_i^+$ exists $r_k \in O_j$ such that. $r \in I_i$.

C3. For each $r_k \in O_i$ we have $R_k^+ \subseteq T_i \cup I_i$.

C4. For each $r_j \in T_i \cup I_i$ exists $r_k \in O_i$ such that $r_j \in R_k^+$.

$S_i(t)$ - *state* of the agent a_i which is the vector of quantities of resources from $T_i \cup I_i \cup O_i \cup E_i$. This vector is indexed by members of resource sets of agent a_i and is varying with time *t*. In this way the state *S(t)* of the whole multiagent system is composed of the states of individual agents: $S(t) = (S_1(t), \ldots, S_n(t))$.

$F_i = \{F_i^{jk}(\bullet), j \in O_i, k \in T_i \cup I_i\}$ - the set of transformation functions which define relations

$$y = F_i^{jk}(x)$$

where y is the amount of internal or input resource r_k necessary to obtain amount x of output resource r_j. Similar transformation functions are defined for internal resources and they describe amount of input resources necessary for obtaining of specified amount of internal resource. In this case such functions are used to describe processes of investment and development.

$M(t)$ - the information available to agent a at time *t*. Generally, it is some subset of the state *S(t)* of agent net obtained with some delay and contaminated by errors.

$D_i(t)$ - the set of strategies of agent a_i at time *t*. These strategies depend on the state $S_i(t)$ and information $M_i(t)$ and can belong to several classes. *Production strategies* define amount of output resources to offer. *Expansion strategies* define amount of internal resources to add to existing ones. *Transaction strategies* involving selection of partner agents to make offer of output resources to, fixing the amount of exchange resource asked for the output resource, choice of partners for obtaining input resources.

2.2 EVOLUTION OF AGENT NETS

Agent Net evolves in continuous or discrete time. Its evolution is driven by transactions between agents. Each agent selects its production, expansion and transaction program according to the set of its strategies and available information. Each transaction involves exchange of input resources for exchange resources which changes the volumes of these resources in possession of agents. Evolution of Agent Net is described in more detail in (Bonatti, Ermoliev and Gaivoronski, 1998).

Agent Nets can be studied using graph theoretical methods and methods used in the study of Discrete Event Systems. There are many open research issues which are discussed together with some properties of Agent Nets in (Bonatti, Ermoliev and Gaivoronski,1998).

3 SYSTEM MODAGENT

In this section we describe architecture of object oriented modeling system MODAGENT which implements the concept of Agent Nets briefly described in the previous section. It is conceived as a tool for modeling of complex distributed systems composed from a heterogeneous population of independent and interrelated agents. Agents are connected by complex dynamical relations of competition and cooperation, exchange products of their activities, receive partial information of the state of the whole system and formulate on its basis the strategies for expansion and survival.

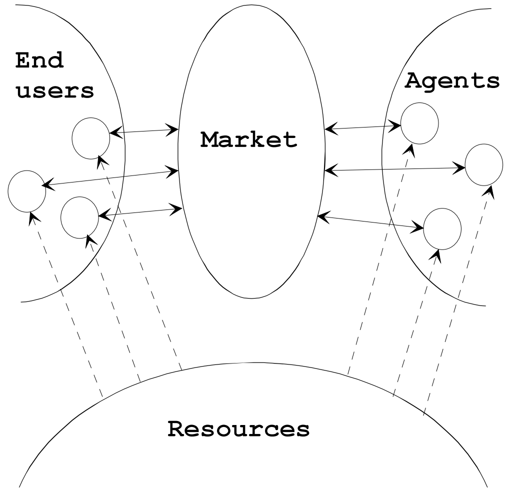
Our primary motivation and application is modeling of business relations in rapidly changing information economy. In this case our agents become enterprises, business units and end users engaged in creation, production, consumption and exchange of products and services of information economy, telecommunication network providers and manufacturers which create infrastructure for information economy. The objective of our effort is to provide tools for evaluation of their strategies. This project was initially motivated by European Telecommunications Standards Institute ETSI standardization activities resulted in detailed analysis of the structure of emerging information economy and described in (Bonatti *et al*, 1996).

MODAGENT shares the methodological approach with system INFOGEN (Bonatti, Ermoliev and Gaivoronski, 1998) developed at the first phase of this project with support of Italtel and constitutes its further development.

Importance of object oriented approach. The complexity of the economic system under study is such that it is unrealistic to pursue an aim of creating a modeling system, which would embrace all problems of interest. What is possible, however, is to create a generic modeling system which structure would reflect the structure of the underlying economy, and which would be endowed with capability of filling this structure with particulars of the given problem. Object oriented approach provides appropriate methodology for doing just this, having the means to define classes, which encapsulate specifics, hiding it from other parts of the system. Moreover, technique of class derivation makes possible to define the generic structure of agents and derive from it specific agents with relatively little effort. In addition, object oriented approach encourages the developer to think in terms of the general structure of application field which result in important feedback to mathematical modeling and applications. These considerations determined our choice of object oriented paradigm for development of MODAGENT which is implemented in C++.

3.1 MODELING CHOICES IN MODAGENT

These will be illustrated in terms of our principal motivation: modeling of information economy. Our approach, however, can be applied to wide variety of complex distributed systems. We explicitly model the



components of economy depicted on Figure 1.

Figure 1: Top Level Structure of `Economy`

- *Resources* are the basic building block of an economy. They are understood in very general terms and embrace all ”passive” entities found in economy: resources in proper sense, products, services, information and derivatives, demand, consumer needs. Resources can be transformed from one into another, exchanged, consumed, accumulated.

- *Agents* is the basic "active" entity of economy. They transform, produce, sell, consume, accumulate, offer, exchange resources, obtain information about economy, formulate and execute strategies in order to fulfil their objectives.

- *End users* are a special kind of agents, which we decided to treat separately for modeling purposes. They consume products and services produced by agents in exchange for money and possibly other exchange resources. In doing so they pursue the aim of satisfaction of their needs;

- *Market* facilitates and organizes exchange between agents and between agents and the end users.

These main components constitute the top level classes of object oriented hierarchy of MODAGENT. In what follows we indicate the names of the classes like **`this`**. The object of class **`Economy`** organizes interaction between objects of classes **`Agent`**, **`EndUser`** and **`Market`** and simulates dynamics of this interaction in discrete time.

Resources can belong to one of five top level classes: `Input`, `Output`, `Internal`, `Demand` and `Need`. Besides, there are exchange resources which are handled by special class `Accountant`. `Input` resources are procured in the `Market` in exchange for exchange resources, are transformed by an agent in `Output` resources using `Internal` resources and offered to the `Market` in exchange to exchange resources. `Need` resources are satisfied by end user consuming `Demand` resources procured in the `Market` in exchange to exchange resources. Thus, resources belonging to `Input` class of one agent may belong to `Output` class of another agent and to `Demand` class of end user. The relations between different resource classes and classes `Agent` and `Market` are shown on Figure 2, similar but simpler relations connect `Market` and `EndUser`.

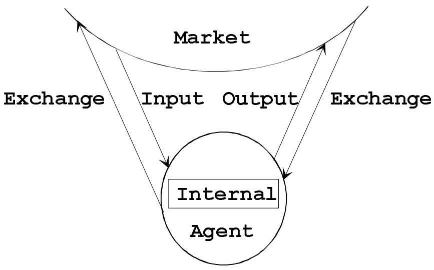


Figure 2: Relations Between Resource Classes and Classes `Market` and `Agent`

The complex relations which connect agents and end users necessitated to make further structuring of `Agent` class into high level subclasses. Besides resource classes `Input`, `Output` and `Internal` mentioned above these classes include:

`Information` handles information available to `Agent`;
`Consumer` procures and handles `Input` resources;
`Producer` transforms `Input` resources into `Output` and handles expansion of `Internal` resources;
`Supplier` handles and dispatches `Output` resources produced by `Agent`;
`Seller` markets `Output` resources;
`Accountant` handles the flow of exchange resources, keep balances and generally keeps track of `Agent` performance;
`Manager` defines policies executed by other members of `Agent`;

The top level structure of `Agent` is shown on Figure 3. Many agents will not possess fully developed components of this structure, in such cases some of components will be empty. Detailed description of MODAGENT structure can be found in (Gaivoronski, 1998).

Another example of multi-agent modeling system is Swarm from Santa Fe Institute (Minar et al, 1996). Compared to Swarm we place much more emphasis on a general way to model agent structure and agent strategies.

4 CASE STUDY: SERVICE PROVISION

This section is dedicated to Agent Net modeling of industrial relations in information industry. In particular, we model dynamics of relations between providers of basic telecommunication services and providers of information services, which are built on top of telecommunication network. This combination may result in complex dynamical patterns of relations between industrial agents, which may include simultaneous competition and collaboration. These patterns are further affected by different industrial strategies of agents resulting from incomplete information in their possession, different relative strengths and weaknesses. These experiments show that the system in its current state allows to perform modeling and qualitative analysis of these phenomena, explore dynamics of agent learning, describe complex relations of competition and cooperation between providers of structural and infrastructural services, highlight role of regulation, evaluate various market strategies.

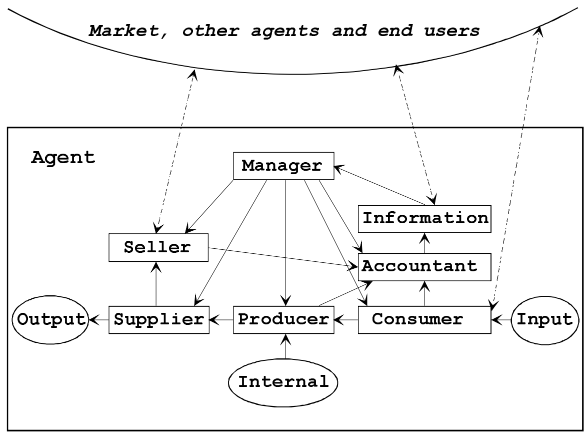


Figure 3: Top level structure of class `Agent`

4.1 PROVIDERS OF INFORMATION SERVICES

The economic system in question is composed from the following agents (see Figure 4).

1. End Users. They have need N_1 which we call here "need for information services" for which satisfaction they have some fixed renewable budget. This need can be satisfied by information services S_1, S_2 and S_3

Service S_1 describes traditional information services which require infrastructural services of telecom network operators and are provided by network operators themselves, like obtaining any kind of information by traditional telephony, yellow pages, etc.

Service S_2 refers to new kind of information services which also require infrastructural services of network operator, but which can be provided both by network operators and independent companies which lease lines from network operator. Think, for example, about Internet based provision of information services.

Service S_3 refers to information service relatively independent from infrastructural services of network operators, like, for example, radio and TV service.

These services are partially substitutable between each other. End users chooses between different services according to the following demand generation model. Attitude of each end user towards any particular service S_i is characterized by service utility function $f_i(x)$ which is nondecreasing function varying from 0 to 1 which defines the fraction of need N_1 satisfied by amount x of service S_i. This function is characterized by two parameters:

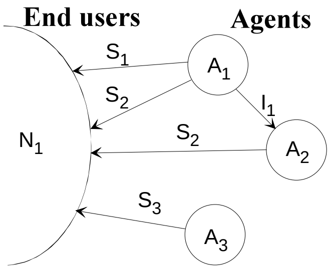


Figure 4: Information Service Provision

a_i - the maximal possible fraction of need which can be satisfied by a given service when its amount x tends to infinity, we assume that all a_i sum up to 1.

b_i - the incremental fraction of the need satisfaction by service S_i for small values of x. End user chooses between services by maximizing his need satisfaction within given budget (perhaps with some error). This permits us to model nonhomogeneous user population with the following service adoption cycle. Suppose that there is some established service and some emerging service. On the early stages of service introduction there will be some fraction of "early bird" users which will adopt a new service even if it costs substantially more than traditional service, it is enough that the new service has some new appealing features. On the later stages the main body of users will adopt the new service, but only if it will become price competitive with the old service. And finally, there will remain some fraction of users which will switch to the new service only if it will become substantially cheaper than the old service.

Normally, there is more than one provider of the same service on the market, which offer service with different prices. We assume, however, that there are more attributes to a service than the price and services from different providers may differ in many other respects, like quality, etc. Thus, not all end users select provider with the cheapest service. However, the price remains important attribute of a service and market quotas of different producers increase and decrease depending on price. This permits us to differentiate between basic service with standard quality and more expensive service with enhanced quality.

Finally, we assume that end users follow with some delay the relative price dynamics of different producers.

2. Producers. There are three groups of producers:

2a. *Provider of structural and infrastructural services A_1*. He provides structural information services S_1 and S_2 and infrastructural service I_1 necessary for provision of S_1 and S_2. We refer to this agent as *Network Operator*.

2b. *Provider of structural services A_2*. He provides information service S_2 for which he needs to buy infrastructural service I_1 from A_1. Alternatively, we refer to this provider as *Information Service Provider*. Thus, he is a competitor of A_1, although in order to compete he needs the service I_1 provided by A_1. Take, for example, as A_2 an Internet provider which leases lines from network operator to provide information services and take as A_1 network operator which is also engaged in provision of information services.

2c. *Provider of structural services A_3*. He provides information service S_3 and is independent from both A_1 and A_2. Think, for example, about newspaper publisher or owner of TV channels. His economic function is to provide a service which can substitute to some extent both S_2 and S_1 in case if they become too expensive or inadequate in some other respect

3. The objectives of economic agents. We assume that end users maximize satisfaction of their needs for information services as described above. Providers maximize their profit by choosing among different strategies. These strategies belong to three classes:

- increase market offer, decrease price and expand provision capacities if necessary;
- decrease market offer and increase price, maybe moving to more specialized market niche;
- keep constant the price and market offer.

Strategies from the same class differ by amount of change of price and market offer. Providers choose between these three strategy classes according to information about the market behavior. If profit increased during current period then the current strategy is maintained or enforced, otherwise the strategy is likely to change. This is done according to *learning process* which uses information about market behavior and is organized similarly to the learning process in the theory of learning automata. That is, each strategy is characterized by probability according to which this strategy is chosen on the next step. These probabilities are updated each period: the probability of strategy which improves some specified performance criterion is increased while probabilities of other strategies are decreased. However, probabilities of all strategies remain positive, which reflects the fact that the profit maximization is the most important, but not unique driving force of agent behavior. Therefore we permit also the keeping of the strategy which leaded to profit decrease, but with smaller probability compared to the case when this strategy increases the profit.

Our objective was to model dynamics of competition and cooperation between providers A_1 and A_2, penetration of service S_2 and dynamics of total market for information services S_1 and S_2. This was studied under different scenarios about market and expansion strategies of both providers, different provision costs for service S_2, different policies of market regulation.

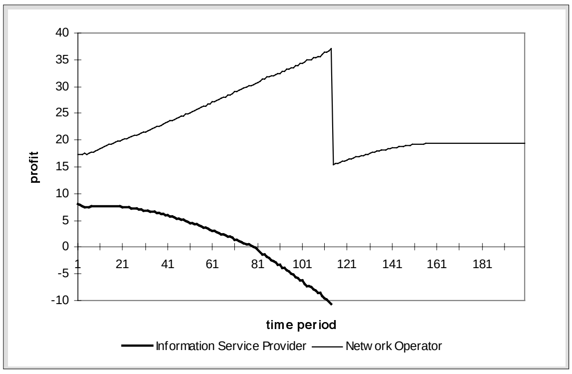


Figure 5: Strong Wins

4.2 SOME RESULTS

Due to the space constraints we can present results only briefly. We observed many interesting phenomena, which have convincing economic interpretations, in particular

- "Strong wins": importance of pursuing aggressive market and expansion policies (for those who can afford them), the provider with strong policies assures himself the largest profit share even with somewhat inferior provision costs; see Figure 5 where the weaker agent is driven into bankruptcy.

- benefits of market regulation which may be performed either by appropriate regulation body or by agreement between providers. Such regulated competition permits to survive providers which offer superior service but can not expand the offer rapidly, in many cases safeguards the total market value and in many cases is beneficial to all players since it stabilizes the market. This case is illustrated by Figure 6 where compared to Figure 5 an upper limit on price for service I_1 was introduced.

- tendency of Network Operator to concentrate on his core business when his information service provision costs are high and his tendency to compete in information services when his costs are comparable with Information Service Provider. Figure 7 gives breakdown of Network Operator revenue for one such case.

- high instability of nonregulated market when everybody pursues strong policies, price wars (Figure 8);

- emergence of qualitatively different dynamical patterns of the system evolution which may include in some cases oscillations in vicinities of different equilibriums and in other cases markedly chaotic behavior.

In this example MODAGENT can be used to identify regions of agent parameters which guarantee “desirable” behavior of economic system.

5 CONCLUSIONS

We presented here the concept of Agent Nets for modeling of complex distributed multiagent systems, described the system MODAGENT for simulation of Agent Nets and provided an example of Agent Net application to study of competition and collaboration between different types of service providers in information industry.

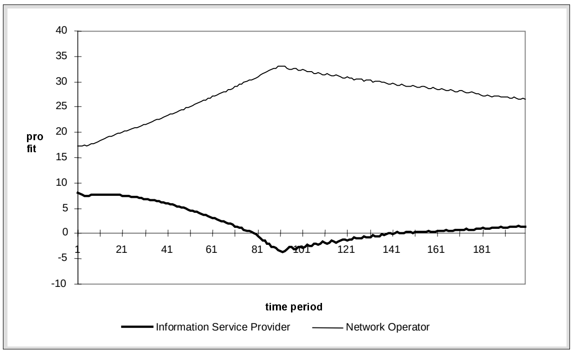


Figure 6: Regulated Price for Leased Lines

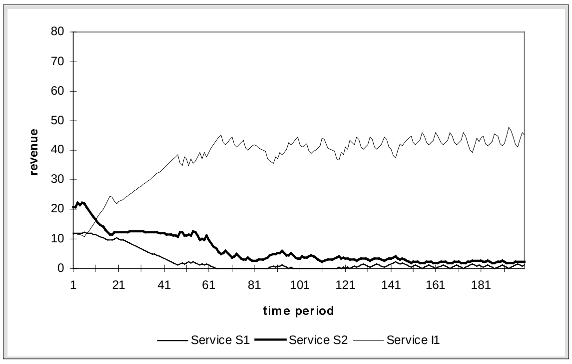


Figure 7: Network Provider Focuses on Core Business

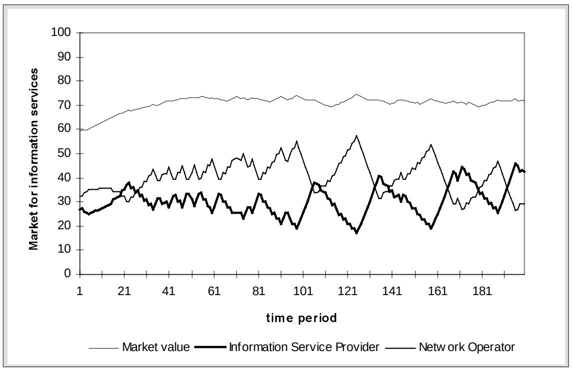


Figure 8: Price War When Both Are Strong

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