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Building multi-agent models applied to supply chain management*†

by

Edward Nawarecki and Jarosław Koźlak

Department of Computer Science, AGH University of Science and Technology
Al. Mickiewicza 30, 30-059 Kraków, Poland
e-mail: {nawar,kozlak}@agh.edu.pl

Abstract: In this paper, a model of a multi-agent system for modelling and optimising supply chains is presented. The most popular methodologies of developing multi-agent systems and selected applications of the agent approach to modelling and optimisation of supply chains are described in brief. A pilot realisation of such a system is also presented, together with a selection of the subsequent experimental results obtained.

Keywords: multi-agent systems, multi-agent methodologies, supply-chain management.

1. Introduction

In the current economic climate, it is very important that the manufacturers have influence on each other so that the possibilities of competition between them are high. This is why an additional support in finding potential partners and forecasting a future state of the market (predicting trends of demand and prices) becomes necessary.

For this class of problems, an application utilising the agent approach seems to be useful. In this approach it may be assumed that entities have their own autonomy or even that cooperating companies provide each other with selected information. Additionally, using the agent approach it may be possible to analyse different solutions for decision and interaction problems.

These are, for example, negotiation, auction and bargaining protocols, planning machine learning, and working with partial knowledge algorithms. A lot of research is presently being carried out in the domain of multi-agent systems concerning the modelling and optimisation of supply chains. They will be outlined in the next section.

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It seems to us that an important feature of a system for modelling and optimising supply chains should be its flexibility, while systems already developed have focused mostly on solving specific problems. The goals of our work concern creation of special agent methodology and models destined to solve a wide range of logistic problems. This is also related to the construction of supply chains. To optimise activities, we applied different approaches, for example, prediction values of different parameters describing the state of simulation or classification of situation patterns. In this work, we concentrate on the analysis of results obtained after simulation of different scenarios selected for different choices of decision parameters.

Other issues include different methodologies for developing multi-agent systems. The development of software is a complex process, charged by the risk of making mistakes in each of the different stages. There are various methodologies of software development, where the choice depends on the specifics of the projects to be realized.

Methodologies of multi-agent system development may be analysed from the point of view of two aspects: As a method for building general purpose software, or as a method for building systems fulfilling special functions of multi-agent systems. In Bergenti, Gleizes and Zambonelli (2004) a comparison between the component approach and agent approach is presented. Attention is given to the possibilities resulting from applying concepts present in multi-agent systems, in the software engineering process. This concerns, in particular, a possibility of using goals to represent the results obtained after agents/components which were called up, have acted.

There is a great deal of methodologies for developing multi-agent systems (Bergenti, Gleizes and Zambonelli, 2004), especially focusing on the phases of analysis and designing and - sometimes - also validation. Some solutions allow a direct passage from the design specification to the implementation phase as a result of code generation. The popular methodologies of MAS development are GAIA (Wooldridge, CityplaceJennings and Kinny, 2000), together with extending methodologies - GAIAv2 and ROADMAP, see Cernuzzi et al. (2004), Tropos (Mylopoulos and Castro, 2000), MASE (DeLoach, Wood and Sparkman, 2001), ADELFIE (DeLoach, 2004), and Prometheus (Padgham and Winikoff, 2004).

These methodologies embrace different steps of the software development process. The majority of them (GAIA, Tropos, MASE) in the first stages are based on the identification of roles played by elements of the system, together with their description, containing performed actions, behaviour patterns, used and modified data, and defined goals, often with their hierarchy with superior and partial goals. Concerning these elements, particular agents are defined which play given roles, have interactions between them and provide the services offered by the system (GAIA).

It is also worth mentioning the AUML (The Fipa..., 2008), which is an extension of UML by elements useful for stages of analysis and design of multi-agent systems. These are: extension of sequence diagrams that have as their goal a better presentation of the specifics of interactions performed with the use of agent interaction protocols and introduction of new elements for class diagrams. A method of presentation offered by AUML might be used by the aforementioned methodologies (for example GAIA).

Methodology designers have been trying to give methodologies universal features, while when solving problems of designed MAS (multi-agent systems), oriented at a specific scope of application, it often turned out that general methodologies contain elements useless in a given case or conversely, do not contain special features, which are required. In this paper we present a methodology of proceeding, adapted to a development for models of supply chains, which take into consideration aspects characteristic for this domain.

Our approach differs from the methodologies referred to. The basic elements are not roles but agents, described by performed actions, goals, used resources and organisational resources.

The second section of the paper contains an overview of application of the multi-agent approach for modelling and optimisation of supply-chains. In the third section proposals of the formal principles of construction of multi-agent environment, oriented at simulation analysis of a given class of supply chains and activities in the production sphere are presented. In the fourth section, we inserted given types of agents, representing distinguished activities of the production process to the abstract structure of the multi-agent systems. The fifth section contains some realisation details and examples of results obtained using the realized environment.

2. Multi-agent systems and supply-chain management

We can find in the literature various models of multi-agent systems for supply-chain management and for modelling supply chain elements, especially for companies and their various departments.

A wider overview of the different solutions can be found in Shen and Norrie (1999) and Moyaux, Chaib-draa and D'Amours (2006). In the former, groups of systems are recognised that concern enterprise integration and supply chain management, manufacturing planning, scheduling and control and holonic manufacturing systems. In the latter, a concept of supply chains, elements that make it up, analysed different forms of cooperation between elements that are parts of the supply chains are defined and examples of multi-agent systems for supply chain management are given.

Examples of multi-agent systems for supply chain management are presented. They are then described considering the researched problem, the applied approach, number of agents and roles played by them. From this overview, one can notice that agents are applied to supply chain management, its construction and coordination. They are used to prevent the Bullwhip effect (Kimbrough, Wu and Zhong, 2001), increase flexibility, for a better choice of business partners and to simulate the emerging global cooperation from local competition. Approaches applied are the evolutionary algorithms for optimisation, agent-mediators, contract-driven coordination, different coordination policies, and analysis of different auction protocols. In the comparison presented here, companies are usually presented by single agents, and only sometimes by more agents.

In Swaminathan, Smith and Sadeh (1998) an environment for modelling the dynamics of supply chains is presented. It consists of structural elements responsible for production and transport and control elements. The production elements contain production agents: Retailer (delivers goods to Customers), Distribution Centre (between Plant and Retailer) and External Suppliers and transport elements contain Transport Agents (represented by transport vehicles).

The control elements contain Inventory Management (Centralised and Decentralised), Demand Management (Market Elements, Prediction Elements), Supply Management (determines times and conditions of the delivery goods), Flow Management (loading of elements, routing of elements) and Information Management (information immediately and periodically accessible).

An important aspect, having an influence on the progress of research on application of multi-agent approach to modelling and management of supply chains, is competition in the framework of Trading Agent Competition SCM (Trading Agent Competition, 2008). In this competition agents participate, trying to build optimal supply chains. The quality criterion used is the amount of wealth gained at the end of the game. The rules of the game are described in Collins et al. (2007), embracing definitions of suppliers, customers and interfaces for companies, which are represented by agents defined by players.

The following aspects of functioning are defined for agents-companies: production (relations between final products and components, required production time and production power), delivery (time needed for the delivery of products in response to requests), storing (taking into consideration inventory costs), and finance (interest charges at the bank for the positive or negative state of the account). For suppliers, conditions are defined for the choice of handling requests to be realized, allocation of production power for requests, which may be only partially fulfilled or requests, which should be realized as soon as possible, daily production value, available production power, reputation and its influence on the agent decisions and the method of determining prices.

The customers are defined by a supply given by the kind of product, quantity, quality, realisation time, maximum price and value of the penalty for the delay.

In the literature, models of agents-companies are presented, especially the ones having succeeded in the competition, their structures and algorithms used. One can distinguish two kinds of architectures of agent-companies: loosely coupled agents, composed of several sub-agents responsible for different aspects of a company functioning, or stronger coupled agents, which have a modular architecture.

For example, in He et al. (2006), the SouthamptonSCM agent is described, composed of three agents: Customer Agent (determines choice of customer request which should be served), Component Agent (determines strategy of components ordering, tracks and predicts prices) and Factory Agent (responsible for the production process according to Customer requests, with some additional products produced in the goal of maximising the utility of the company).

In Benisch et al. (2004) an agent with modular structure is presented, composed of a Modelling Module (describes other agents), Bidding Module, Scheduling Module, Delivery Module, Component Inventory with Procurement Module and Factory with Product Inventory. In Pardoe and Stone (2007) the TacTex06 agent is presented, consisting of the following essential modules: Supplier Model, Supply Manager, Demand Manager, Demand Model as well as OfferAcceptancePredictor.

Agent Mieux (Benisch et al., 2006) has emphasis on the strict coordination between bidding, buying components and planning with the intention of being able to adapt quickly to changes on the market. Its components are: Strategy Module (determines a part of the predicted demand, which the agent should try to fulfil by its offer, and determines when given products related to given requests are produced), Scheduling Module (manages a predicted production plan within a time frame of a few days), Bidding Module (determining a willingness of gaining a bidding for the given bidding price), and Procurement Module.

3. Methodological aspects

From a functional point of view, a problem of multi-agent system design may be considered in a variety of ways and it seems that the following dual characteristics can be pointed out:

- design of the system, whose role will be included in cooperation with the existing real system for the goal of recognising its features, improving its functionality or supporting the decision process,
- the design of the multi-agent system that works in a virtual computational environment and that has to provide information concerning the functioning of a certain real system to make it possible to ascertain a more precise recognition/searching process currently happening in it and existing relations, which form the basis of improvement of its functioning, assessment of decision strategies or the necessary analysis of the risk of anomalies and critical situations appearing as well as methods of reacting in response to them.

It is worth noting that although functionality of designed multi-agent systems differs as to the above-mentioned aspects, the process of design and of its partial realisation contains a lot of common elements. So, in both cases it is necessary:

- to possess some "a priori" knowledge about the real life process for which a multi-agent system was designed;
- to create a concept of roles realised by particular agents taking into consideration certain features of the environment (real or virtual) where they have to function;
- to design agents appropriate for the tasks, which are assigned to them;
- to design a hardware and software infrastructure which makes it possible to realise a designed system.

An important difference for these cases is the fact that in the first case a multi-agent system is adjusted to the existing environment and the structure of the real process and in the second case there exists a significant freedom in shaping the environment of agents. Additionally, the problem of monitoring and, in consequence, exchanging and the initial processing of data should be solved in a different manner.

In the second case, a problem of designing the model, which not only supports decision processes, but also simulation of the real system becomes a key problem. In some cases, a good choice may be to join together both functionalities, that is, to develop a virtual agent model which cooperates with an agent-oriented real system.

The analysis carried out in this work is aimed mostly at the second case of the use of multi-agent systems, that is, a construction of a model which makes it possible to carry out research on the behaviour of a real system under different conditions of its functioning and different strategies of agents of which it is built.

The general model of a system is constituted by the equation

$$Sys \equiv \langle Ag, Env, Res, Com, Org \rangle \tag{1}$$

where:

Ag – set of agents,
Env – environment,
Res – resources accessible in the environment,
Com – communication,
Org – organisation, which determines relations between the agents and between the agents and the environment.

External agent models will be analysed at system level, making it possible to adjust rules, common relations, and relations with the environment.

$$A_i \equiv \langle X_i, T_i, R_i \rangle,\ A_i \in Ag \tag{2}$$

where:

$X_i = \{x_1^i, x_2^i, \ldots, x_n^i\}$ – set of actions (activities) of agent A_i,
$T_i = \{t_1^i, t_2^i, \ldots, t_m^i\}$ – goals of agent A_i,
$R_i = \{r_1^i, r_2^i, \ldots, r_m^i\}$ – resources of agent A_i, $R_i \subseteq Res$.

Moreover, the effect of applying a sequence of actions is estimated through a quality function of reaching a given goal:

$$F_i(t_k^i) = F_i^{t_k}(x_j^i(n)), \quad n = 1, ..., N, \quad t_k^i \in T_i, x_j^i \in X_i \tag{3}$$

where:

$x_{ij}(n)$ – action of agent i at the n-th stage of its functioning,

N – planning horizon.

An overall estimation of the functioning of the agent may be determined, for example, as a weighted sum of given evaluations for partial goals, $t_k^i \in T_i$.

A description of the environment (Env) depends significantly upon the features of the modelled real system, which is why representing it in the general form encounters difficulties. For an analysis it seems to be useful to express an environment as follows:

$$Env \equiv \langle E, Y : Y \to Res \rangle \tag{4}$$

where:

E – a metric/graph space which represents a structure of possible activities, realised by agents:

$$E = (Ag \times Ag) \to \{0, 1\} \tag{5}$$

Y – a relation mapping a location in a space E expressing an accessibility of resources Res

$$Y = (Ag \times R) \to \{0, 1\}. \tag{6}$$

Resources will be described by:

$$Res \equiv \langle R, Y^{-1} \rangle \tag{7}$$

where:

$R = \{R_1, R_2, \ldots, R_n\}$ – types of resources available in the system,

Y^{-1} – a relation inverse to Y, assigning locations in the environment to resources.

Similarly, communication may be described by:

$$Com \equiv \langle Z, C \rangle \tag{8}$$

where:

$C = \{C_1, C_2, \ldots, C_l\}$ – communication means accessible in the system,

Z – a relation assigning a given communication means to agents, that is

$$Z = (C \times Ag) \to \{0, 1\}. \tag{9}$$

Construction of a description of the organisation (Org) of a multi-agent system plays an important role. Here it is also possible to build a wide variety of formalisms, adjusted to the specificity of an analysed system. For a class of processes analysed in the next sections of the paper, it is proposed to accept that the organisation is represented as a triple:

$$Org \equiv \langle B(Res), D(Com), M(Ag) \rangle \tag{10}$$

where

$B(Res)$ – a relation defining conditions of access to resources,
$D(Com)$ – a relation defining conditions of access to communication,
$M(Ag)$ – a set (collection) of mutual relations between agents.

Then:

$$B(Res) = \{(R_1, W_1), ..., (R_r, W_r)\} \tag{11}$$

where:

(R_i, W_i) – defines a condition of access to resource i

Similarly:

$$D(Com) = \{(C_1, V_1), ..., (C_l, V_l)\} \tag{12}$$

where:

(C_j, V_j) – determines access conditions to communication means j.

Interpretation of access conditions (W_i, V_j) depends on a given analysed task. For example, (R_k, W_i) may define a quantity of the k-th resource made available to agents during one stage of the process (i.e. for the execution of one action). Similarly, (C_k, V_j) may determine a preferred size or frequency of messages sent using a given communication method.

Relations between agents may be described as follows:

$$M(Ag) \equiv (Ag \times Ag) \rightarrow M \tag{13}$$

that is, by a mapping of a set of pairs (A_i, A_j) to a set of possible mutual relations. This may be written also as follows:

$$M(A_i, A_j) \rightarrow m_{ij} \tag{14}$$

where $m_{ij} \in M$, m_{ij} - a mutual relation between agents A_i and A_j.

Among the possible relations (m_{ij}) one can distinguish, as characteristic ones: equivalence, domination (partial and complete), co-dependency (cooperation, competition), and antagonism.

Equivalence may be defined as:

$$A_i \leftrightarrow A_j \equiv (A_i \leftrightarrow A_j) \rightarrow (X_i = X_j) \wedge (T_i = T_j) \tag{15}$$

and, following (3):

$$F_i^{t_k}(x_k^i(n)) = F_j^{t_k}(x_k^j(n)),\ \forall t_k \in T_i = T_k. \tag{16}$$

It means that a consequence of (16) is the application of the same estimations of the functioning of agents A_i, A_j for each goal t_k.

The relation of domination is described by the expression:

$$A_d > A_i \equiv (A_d > A_i) \rightarrow \exists t_k^i \in T_i : F_i^{t_k}(x_j^i(n),\ x_l^d(n)),\ x_j^i \in X_i, x_l^d \in X_d. \tag{17}$$

It means that the effect of the actions of the i-th agent depends not only on its own but also of the arbitrarily enforced actions of the dominant agent (A_d).

The full dominance concerns all goals of agent A_i

$$A_d >> A_i \rightarrow \forall t_k^i \in T_i : F_i^{t_k}(x_j^i, x_k^d). \tag{18}$$

Relation of co-dependency may be described similarly to (17), but such a relation has a mutual character, which means that actions of A_i, A_j have influence on the evaluation of activities of each of them.

Taking additionally into consideration the concordance or divergence of goals of the pair of agents (A_i, A_j) one can introduce the following formulations concerning cooperation, competition and antagonism.

Co-dependency may be described in few variants:

cooperation:

$$A_i \diamondsuit A_j \rightarrow \exists (t_k^i, t_m^j) : \begin{cases} F_i^{t_k}(x_j^i, x_m^j) \\ F_j^{t_n}(x_j^i, x_k^j) \end{cases} \tag{19}$$

which means that such a pair of goals of agents A_i and A_j exists, for which their evaluation depend on the actions of both agents.

competition:

$$A_i \sim A_j \rightarrow \exists (t_k^i = t_m^j) : F_j^{t_k}(x_j^i, x_k^j) \tag{20}$$

which means that a pair of goals of agents (A_i, A_j) exists, for which there is a set of identical quality coefficients, dependent on the actions of both agents.

antagonism:

$$A_i \oplus A_j \rightarrow \exists (t_k^i, t_l^j) : F_k^{t_n^i} = -F^{t_m^j} \tag{21}$$

full antagonism:

$$A_i \otimes A_j \rightarrow \forall (t_k^i, t_l^j) : F_k^{t_n^i} = -F^{t_m^j}. \tag{22}$$

In the latter cases a direct contradiction of interests exists for at least one pair of goals (antagonism) or all the goals (full antagonism).

Relations between agents, mentioned above, make it possible to define precisely the strategies for activities appropriate for them and to assess the functioning of the whole system. An occurrence of given relations also has an influence on a method of defining a global criterion of quality of the system functioning, which may be expressed in the form:

$$G(S) \equiv G(X, R, T) \tag{23}$$

where:
$X = (X_1, X_2, \ldots, X_n)$ – space of agent action,
$R = (R_1, \ldots, R_m)$ – resources of the system,
T – a global goal of system functioning.

With the notions introduced we may start describing the functioning of the multi-agent system and processes (local and global) related to it. The functioning of an agent is described by its strategy:

$$\text{Str } A_i \equiv \{x_j^i(n)\}, \quad x_j^i \in X_i, \quad n = 1, ..., N \tag{24}$$

where:
$x_j^i(n)$ – j-th action of agent A_i in the successive stages $n \in \{1, \ldots, N\}$ of system functioning,
N – an accepted planning horizon.

The following action, and in consequence, the whole strategy, are selected by the agent on the basis of its decision algorithm:

$$\text{Alg } A_i \equiv \text{Alg } [T_i(n), X_i(n), F_i(t_i), Res^{A_i}(n)], \quad T_i(n) \in T_i. \tag{25}$$

Most often Alg may be used to search for extrema:

$$\text{Alg } A_i \equiv \max_{x_i(n) \in X_i} [F_i(n) \,|\, t_i \in T_i], \quad R^{A_i}(n) \in Res^{A_i} \tag{26}$$

where:
$R^{A_i}(n)$ – resources available for A_i in a stage n,
$F_i(n)$– quality function of goal realisation t_i .

4. Agent model of system for the management and optimisation of supply chains

Using the elements of the general model of multi-agent system, presented in the previous section, description of the multi-agent system for modelling and optimisation of supply chains was done. This system is modelling the behaviour of a company, market (represented by Agent Market) and customer (represented by Agent Customer).

The company is represented by several agents such as: Seller (responsible for selling of final goods), Buyer (responsible for buying components), Inventory Manager (performs management of the stocks), Producer (performs the production process), Strategy Planner (responsible for determining the strategy of the company functioning). All agents, being the parts of the company, are subordinate to the Strategy Planner agent, determining strategies and modifying the goal functions of agents. However, the agents also have a high degree of autonomy. Because of the possible appearance of unpredicted situations and the knowledge possessed, both partial and uncertain, the agents may be forced to react, including a change in their goals and plans, within the given constraints.

Fig. 1 shows relations of co-dependency between agents, and Fig. 2 — relations of antagonism and domination.

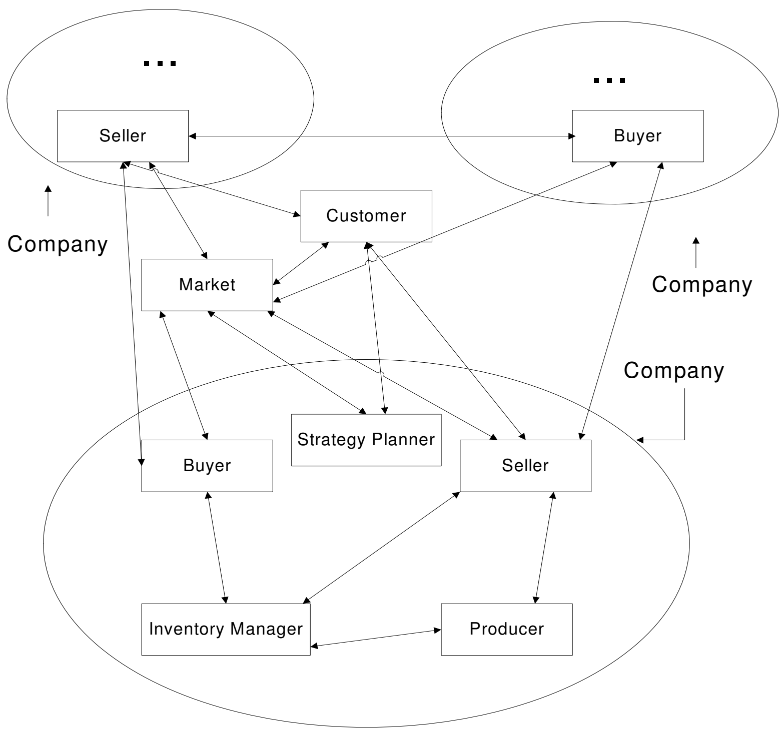

Figure 1. Relations between agents: co-dependency

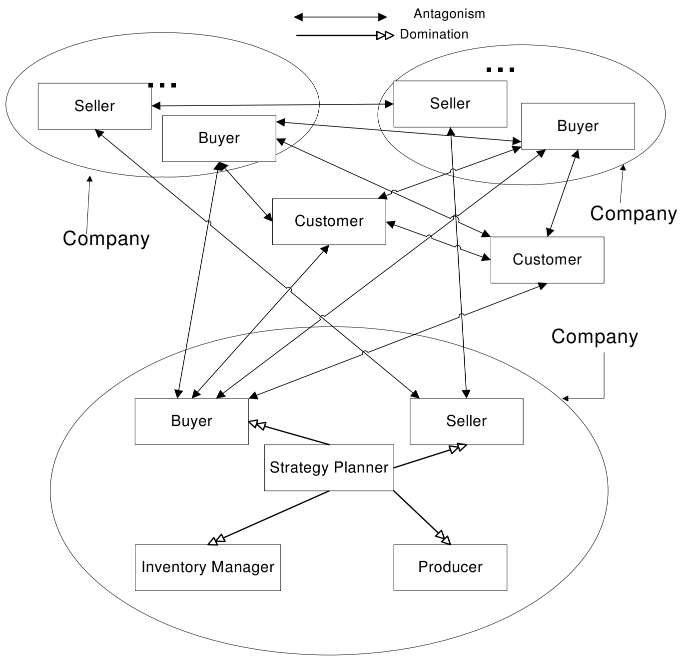

Figure 2. Relations between agents: antagonism and domination

4.1. Agent Customer

Agent Customer (*Cust*) represents a final customer, ordering goods produced by the company. It cooperates with Agent Market, effecting contracts of buying/selling and Agent Seller, making the final products available.

Actions. Agent Customer performs the following actions

$$X_i = \{SD, GIBC, GG, CG\} \tag{27}$$

where:

- *SD* (send demands) – announces a demand for goods to Agent Market,
- *GIBC* (get info about buying contract) – receipt of information regarding an established contract of buying from Agent Market,
- *GG* (get goods) – receipt of goods transferred by a given Agent Seller
- *CG* (consume goods) – consumption of possessed goods according to the function defined for the agent.

Possessed resources. Agent possesses different kinds of final products $product_i$, not yet consumed, and financial means:

$$R_i = \{money, product_1, \ldots, product_n\}$$

Goals. Goals $T_i = \{G\text{-}UTIL\}$, where $G\text{-}UTIL$ is the utility function of agents. The value of $G\text{-}UTIL$ is determined by values of resources possessed by agent currently and previously consumed.

$$F(G\text{-}UTIL) = \sum_{t=0}^{n} \alpha^{n-t} u_t(R_i) \tag{28}$$

where t – time, n – current time, $u_t(R_i)$ – function, evaluating the quality of the configuration of resources owned in a given time, α – coefficient, $0 < \alpha < 1$.

Relations between agents. Agent Customer is in the relation of co-dependency with Agent Seller and Agent Market, and in antagonism with other agents: Agent Customer and Agent Buyer.

4.2. Agent Market

Market (*Mar*) associates requests of buy and sell coming from agents Buyer, Customer and Seller.

Actions. Actions of Agent Market:

$$X_i = (RCVSO, RCVBO, DICB, DICS) \tag{29}$$

where:

- *RCVSO* – receives a sale offer;
- *RCVBO* – receives a buying declaration;
- *DICB* – delivers a list of associated orders of buying/selling to a Buyer/Customer,
- *DICS* – delivers a list of associated orders of buying/selling to a Seller.

Goals. Goals are defined as follows: $T_i = \{F_i(G\text{-}MAXGT), F_i(G\text{-}MAXMT)\}$, where:

- *G-MAXGT* – try to obtain maximum possible goods transfer,
- *G-MAXMT* – try to obtain maximum possible money transfer.

and $F_i(G\text{-}MAXGT)$ may be expressed as a sum of the all exchanged goods and $F_i(G\text{-}MAXMT)$ as a sum of the all exchanged financial means.

Relations between agents. Agent Market is in the relation of co-dependency with Agent Sellers, Agent Buyers and Agent Customers.

4.3. Agent Seller

Agent Seller (*Sel*) sells goods on the market. To do this, the agent submits offers to the market and after confirmation of transaction obtains goods from the storehouse handled by Inventory Manager Agent and hands them over to the Buyer or Customer Agent.

Actions. Agent has a following set of actions

$$X_i = (PSELL, GGOODS, SGOODS, ECOND), \tag{30}$$

where:

- *PSELL* (propose sell) – sends a proposal of goods sale to Agent Market, the proposal depends on the current state of the stock, goals and the situation on the market,
- *GGOODS* (get goods) – gets goods from warehouse,
- *SGOODS* (send goods) – sends goods to a purchaser – Agent Buyer of another Company or Customer,
- *ECOND* (estimate condition) – determines (considering current goals, state of stocks and state of the market) what transaction conditions are possible,
- *SETGOALS* (set goals) – sets configuration of goals taking into consideration information obtained from Strategy Planner.

Resources possessed by Agent Seller are the final goods in the warehouse:

$$R_i = \{finalproduct_1, ..., finalproduct_m\}.$$

Goals. Set of goals of agent $T_i = \{G - SG, G - MG\}$ contains the following elements:

- $G-SG$ (sell goods) – sends final goods owned by the company, a constraint is minimal selling prices set by the Agent Strategy Planner,
- $G - MG$ (maximise gain) – sends goods in such a way that gains are maximised.

Relations between agents. Agent Seller is in the following kinds of relations:

- domination – the agent is dominated by the Strategy Planner, which sets it goals,
- antagonism – goals of the agents are opposite to the goals of Agent Sellers of other companies,
- co-dependency
  - Agent Customers and Buyers – number of goods sold and realisation of goals depends on the agents Buyer and Customer which submit their needs for the goods,
  - Producer – delivers final products to warehouse, which determines the number of goods which may be sold,

– Inventory Manager – determines the number of ordered components and in consequence the number of produced final products.

4.4. Agent Buyer

Buyer (*Buy*) – places orders for goods needed, in interactions with the market role, and, after a transaction of buying, it places goods in the warehouse managed by InventoryManager.

Actions The actions associated with the agent

$$X_i = (\mathit{WILBUY}, \mathit{SENDORD}, \mathit{CONFTR}, \mathit{GETG}, \mathit{SETG}) \tag{31}$$

where:

- *WILBUY* (estimates willingness of buying) – calculates a willingness of buying of goods depending on the directives set by Strategy Planner, information about the market state, proposed price and needs notified by Inventory Manager.
- *SENDORD* (places orders) – sends buying offer to Market,
- *CONFTR* (confirm transaction) – confirms the conclusion of the transaction,
- *GETG* (get goods from seller) – gets goods from the agent Seller,
- *SETG* (set goals) – sets configuration of goals on the basis of information obtained from Strategy Planner. The purchase may be urgent (a production stoppage - so there is a risk it will happen) or ordinary (the need to replenish stocks to a desired level).

Resources possessed by the agent: $R_i = \{money\}$ – includes the quota of money reserved to be at the disposal of the agent, purchased goods are transferred directly to the warehouse.

Goals. Goals of agent $T_i = \{getcomponents(time)\}$ consist of purchasing the defined number of goods in given times (*time*). The quality of goal realisation depends on the number of purchased goods compared to the number needed and potential delays of component arrival: $F_i = \{quantities(t), delays(t)\}$.

Relations between agents. Agent Buyer is in a co-dependency relation with the following types of agents:

- Agents Sellers of other companies,
- Inventory Manager, which decides the number of goods required.

It is also dominated by Strategy Planner, which determines the prices the agent should be willing to pay for given times of goods delivery and given degree of urgency of purchasing goods, and in relation of antagonism with Agents Buyers of other Companies and Agents Customers.

4.5. Agent InventoryManager

InventoryManager (*InM*) informs Buyer, which components should be bought and predicts demand.

Actions. Actions performed by the agent are:

$$X_i = (PREDDEM, SENDNEEDS, EST\text{-}COSTS, SETG) \tag{32}$$

where:

- *PREDDEM* – predicts future demand and on this basis determines current required purchases,
- *SENDNEEDS* – sends needs to agent Buyer for purchase of given goods, taking into consideration the number of elements, delivery time and urgency of order.
- *EST-COSTS* – predicts storage costs, influencing preferred inventory levels,
- *SETG* – sets configuration of goals considering information obtained from Strategy Planner.

Resources. The resources owned by these agents are the components and final products stored in the warehouse:

$$R_i = \{component_1, \ldots, component_n, final-product_1, \ldots, final-product_m\}.$$

Goals. The goals of agent Ti embrace the following aspects: to guarantee the preferred levels of stock (components and final products) in the storehouse and conform to the strategies chosen by Strategy Planner and existing stocking costs $T_i = \{$*get-components, limit-costs, service-products*$\}$, $F_i = \{$*costs, preferred-number-of-comp, preferred-number-of-products*$\}$.

Relations between agents. Agent Inventory Manager is dominated by Strategy Planner, which chooses its strategy and is dependent (in relation of co-dependency) upon following agents:

- Buyer – its activities influence the number of purchased components,
- Seller – its activities influence the number of the final products sold,
- Producer – delivers final products to the warehouse.

4.6. Agent Producer

Producer (*Prd*) – performs a production process; on the basis of available actions and resources (components, production lines) possessed performs production of output goods, which are being sold by Seller.

Actions of the agent are as follows:

$$X_i = (OEDPROD, PRODUCE, GETCOMP, PUTPROD) \tag{33}$$

where:

- *ORDPROD* – defines conducted production,
- *PRODUCE* – performs the production of final goods from input components,
- *GETCOMP* – gets components from the storehouse,
- *PUTPROD* – delivers final product to the storehouse.

Resources. The agent has the following kind of resources at its disposal: $R_i = \{production\_lines, products, components\}$

Goals. Goals T_i of agent concerns the carrying out of production according to specifications obtained:

$$T_i = \{\textit{produce-according-specification}(\textit{quantity}, \textit{time}, \text{it quality})\}$$
$$F_i = \{\textit{fulfil-needed-requests}\}.$$

Relations between agents. Agent is dominated by Agent Strategy Planner, which determines production strategy, and in the co-dependency relation with the following types of agents:

- Agent Seller – number of sold elements influences production level,
- Agent Buyer – number of bought components influences production capacity.

4.7. Agent Strategy Planner

The Agent Strategy Planner manages other agents, representing parts of the company and the configuration of their goals, choice of the production strategy (associated with the preferred level of stocks) and choice of the price ranges offered during buying and selling.

Actions are defined as follows:

$$X_i = (\textit{SPROD}, \textit{SSTORAGE}, \textit{SBUY}, \textit{SSELL}) \tag{34}$$

where

- *SPROD* – sets production strategy,
- *SSTORAGE* – sets storage strategy,
- *SBUY* – sets components purchasing strategy,
- *SSELL* – sets final goods selling strategy.

Resources. The agent is in the direct possession of financial means $R_i = \{money\}$.

Goals. The goals of agent are described as follows:

$$T_i = \{\textit{G-MAXPROF}(t), \textit{PREST}(t, \textit{AgSet}, \textit{prest-constr})\} \tag{35}$$

where $\textit{G-MAXPROF}(t)$ is maximisation of the possessed financial means in the given time horizon t, $F_i(\textit{G-MAXPROF})$ is a function of prediction of financial means in the given time $t' \leq t$, and $PREST(t, AgSet, prest\text{-}constr)$ means that in the given time range the value of evaluation of prestige by A_i regarding agents $A_j \in AgSet$ will not drop below the values *prest-constr*. The agent calculates prestige of other agents, which has influence on actions regarding them, here the agent A_i tries to estimate how it is perceived by other agents.

Relations between agents. The agent dominates other types of agents in the company (Seller, Buyer, Inventory Manager, Producer). It is also in the co-dependency relation with agents Customer and Market, and in relation of antagonism with other companies (assuming limited market absorption).

5. Description of realisation and selected results

5.1. Realisation

In the framework of research already carried out there have been several pilot implementations of environments for modelling and optimisation of supply chains performed by our group. (Koźlak, Dobrowolski and Nawarecki, 2007, and Koźlak et al., 2007). The concept of one of them and the two pilot realisations based on it will be described here. The systems were programmed in Java language with the support of the agent platform JADE (Jade, 2008).

The company objective was to maximise profit. Various decision parameters, describing the configuration of the production processes specified particular activities: For the given production lines the following were taken into consideration: production capacity, quality, maintenance costs. For buying of components, the parameters used were: mark-up, cost and time of realisation, quality of products and prestige of contractor. For the selling process: prestige, ordered quantity and time taken to realise the request.

The choice of the optimal decision parameters is done using simulation of scenarios. An agent generates a population of individuals with given decision parameters and performs simulation with an assumed time span starting from the current state of the market with fixed parameters of clients and other producers that do not change their strategies. Using an evolutionary algorithm, the best set of decision parameters (estimated by the wealth of a company) is selected and the simulation for these parameters is performed.

5.2. Systems architecture

In the framework of the study, two pilot systems were implemented, with functionalities based on the presented model. The first one focused on elements related to the decision making process of agent-company and parameters influencing it, description and configuration of production capacities, and optimisation of these parameters with the use of heuristic algorithms (for example evolutionary algorithms), Koźlak, Dobrowolski and Nawarecki (2007). The second system focused on the application of a market–mediator agent for concluding transactions and setting conditions, as well as research resulting from applying different stock management strategies (like ATO and MTO). Fig. 3 shows dependencies between agents.

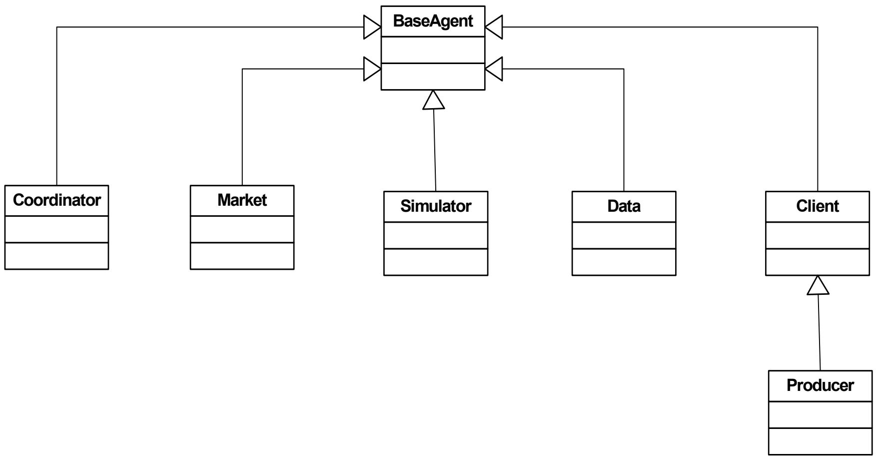

Figure 3. Classes of agents

The tasks of agents presented in Fig. 3 are as follows:

Base Agent – offers basic functions used by each agent,
Data Agent – responsible for picking configuration data from database and storing statistics about running of the system,
Coordinator Agen – registers created agents and provides information about offers of companies for given kinds of goods,
Simulator Agent – responsible for the synchronisation of activities, verification of whether the system is ready to pass to the next step and move into simulation steps (steps representing consecutive days),
Market Agent – responsible for leading the negotiation process between agents by ordering and offering goods, and for determining the outcome of negotiation,
Agent Client – represents a customer,
Agent Company – represents the whole company.

One can note that the model is realised on a more general level than the one presented in the model described in Section 4. We decided that in the pilot realisation, the choice of such a level of generality is justified, because it facilitates the interpretation of results. In the next versions of the system, we are planning the realisation conform to the presented model.

5.3. Selected results

The choice of results is motivated by presentation of different features of the implemented system, whose fundamental elements were given in the previous section.

Below, three experiments are presented, which show:

- influence of production capacity of some companies on the wealth of all companies,
- the determination of the wealth obtained as a result of the evolutionary optimisation,
- the change of customer preferences and its influence on the advantages of using given production strategies by the companies

The model presented is highly configurable, with the possibility to set many parameters related to the description of goods, production lines, prediction algorithms, decision schemes of agents. Because of the high level of detail, the majority of these parameters are not provided in this work.

5.3.1. Influence of the increase of production capacity

We shall now focus on a change of the company profit after the increase of production capacity of some companies. The tests were performed for 12 agents that produced element types A, B, C, D, and E (see technology tree in Fig. 4). There were two agents, each producing technologies A, B, C, D, and four agents producing product E. In each round, orders were sent to producers, and it was assumed that the quantity of the requested goods was higher than the production capacity of the agent. Each agent had differently configured parameters describing production processes and negotiations. For example, in the initial configuration: agent E0 had a low production capacity but a more advantageous offer, E1 has a high level of prestige and a production strategy which fits within the market needs, E2 relatively low production power, low production quality, average cost and low mark-up, E3 the highest production capacity, high quality and high line maintenance costs. The best results among the agents of this type were obtained by agent E1, followed by E0, E2 and E3.

An initial analysis (Fig. 5) shows a low profitability of companies.

The reason of this situation is the small productivity of companies D0 and D1, which are not able to deliver a sufficient quantity of components D, for which there is a very high demand (the ratio of components C to D is equal 1 to 3). To confirm this, for the next tests an increase was applied of both the production capacities of companies D0 and D1 (D0: from 26 to 170, D1: from 43 to 100) and of the acceptable percentage of exceeding them (D0: from 20% to 70%, D1 from 31% to 80%), while other parameters remained fixed. The results of Fig. 5 confirm this proposition.

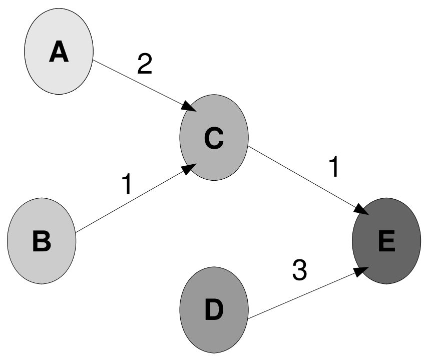

Figure 4. Technology tree

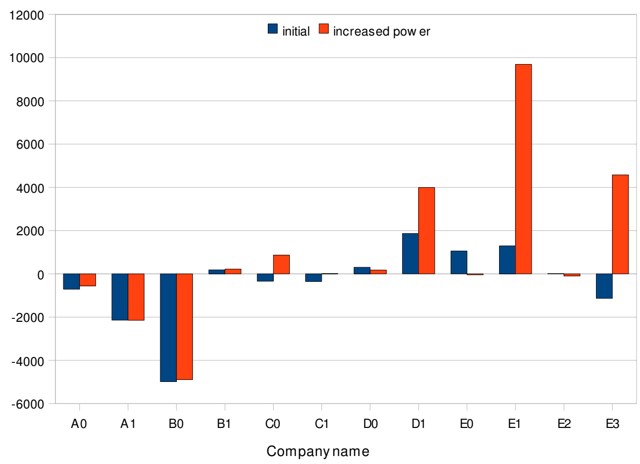

Figure 5. Profitability for a case in increased production capacity

5.3.2. Optimisation of decision parameters

The results of optimisation of decision parameters with the fixed states of the environment are presented below. The values of the quality function obtained by the individuals in the evolutionary algorithm (Fig. 6) and an increase of the quality of the best individual (Fig. 7), are shown.

We can notice that the value of income obtained by a company with the strategy being optimised is gradually increasing.

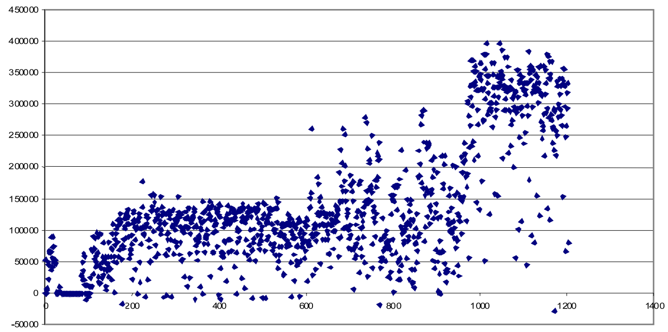

Figure 6. Quality function values of individuals in the evolutionary algorithm, the individuals represent companies with given values of decision parameters. x-axis - quality value, y-axis - simulation time

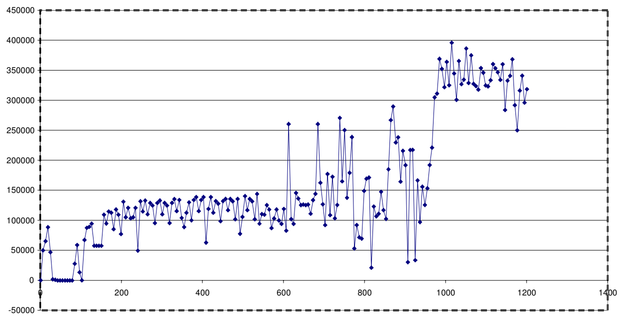

Figure 7. Quality function values of the best individuals during simulation: x-axis - quality value, y-axis - simulation time

5.3.3. Choice of production strategy

The subsequent experiments (Figs. 8, 9, 10, 11, 12) concerned a change of the customer preference and its influence on the advantages of using the given production strategies by the companies. The two companies producing one kind of finished goods are considered.

Different production strategies may be suitable for the given parameters associated with production time of particular components, production costs, length of time in the warehouse and the variability and time periods of how long the customers are willing to wait for their delivery. During the experiments we took into account two strategies - ATO (Assembly-to-Order) and MTO (Make-to-Order). In the ATO strategy, it is assumed that the components for the production of the final products are stored in the warehouses in

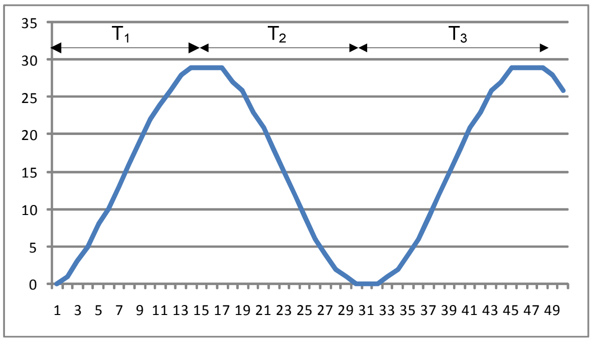

Figure 8. Demand for final product in weeks

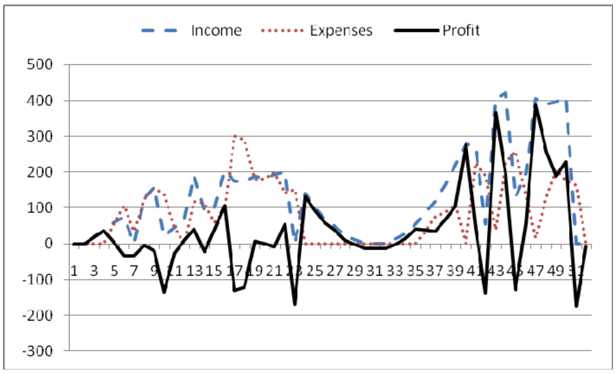

Figure 9. Company A1: Profit, income and expenses in weeks

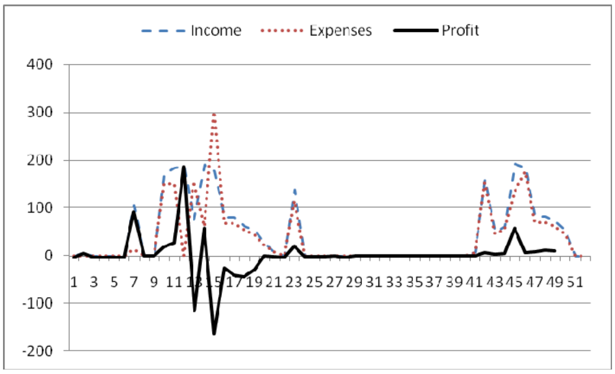

Figure 10. Company A2: Profit, income and expenses in weeks

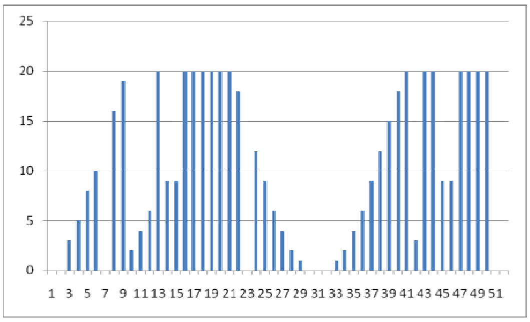

Figure 11. Sale of Company A1 in weeks

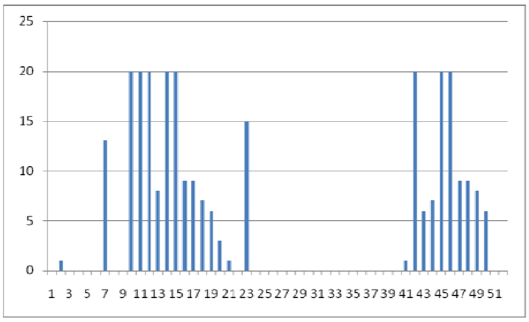

Figure 12. Sale of Company A2 in weeks

order to guarantee production continuity, taking into consideration the predicted demand level. For this goal, the elements of the stock level required are taken into consideration (for example, cycle stock for guaranteeing the realisation of demand at a usual level, and safe stock levels which minimise the danger that a sudden big order is not fulfilled). The ATO strategy gives the possibility of a speedy realisation of the customer's requests, however, different costs for maintaining the inventory stock have to be born. The second analysed strategy, MTO, is based on the principle that the components of the final element are ordered only after the customer request arrives. In this case, the time period needed to realise the customer request is higher, whereas the costs are lower due to the lack of storage costs. The risk associated with making the time of realising customer request longer is that the customer may become discouraged and give up on the purchase.

Fig. 8 shows the demand for the final product. In this figure time periods T_1, T_2 and T_3 are marked, each of them is characterised by different behaviour of customers. In T_1 the demand increases until reaching the maximum, in T_2

the demand decreases and in the half of T_2 the preferences of the customers are changed. At the beginning, the low costs of goods are more important for customers selecting the offers than delivery time, after, the delivery time becomes more important. In T_3 the demand increases again. In fig. 9 and fig. 10 the evolution of profit, income and expenses for companies A1 and A2 are presented. Profit is calculated as follows: from the income, expenses (costs of buying components), storage costs and penalties for not fulfilled concluded contracts are deducted. For the clarity of the figures, storage costs and penalties, which are much smaller then profits, incomes and expenses, are not presented. Fig. 11 and Fig. 12 show the levels of sale for both companies.

Company A1 sells goods using ATO strategy and Company A2 uses MTO. In the period T_1, Company A2 has results better than Company A1, having a comparable level of sales and lower costs (lack of store costs). The cumulated profit in T_1 period equals −22 for company A1 and 79 for company A2, income: 1195 for company A1 and 1178 for Company A2 and expenses: 1051 for Company A1 and 901 for Company A2.

The results of Company A1 during T2 are similar to the results in the period T_1 (incomes: 1502, expenses 1450, profit: -69), for Company A2 the income and profits decrease, in high degree because of the change of customer preferences (incomes: 372, expenses 312, profit: -98). In T3, with customer preferences less favourable for MTO and the increase of demand for product as well as the increase of prices demanded by the company A1, the Company A2 (income:952, expenses:820, profit:117) becomes permanently less competitive than Company A1 (income: 4038, expenses: 2081, profit:1837) .

6. Conclusions

The main part of the results contains a proposal of a methodology for constructing multi–agent systems, oriented at the simulation analysis of the supply chains. The goal is to explicitly present the general rules of behaviour of the system and its features, which become important for the next steps of system development, like for example, implementation and evaluation of results. We applied the proposed methods for modelling and simulation analysis of supply chains. Agents from this domain were described, using the presented methodology. The approach was used to realise a few pilot simulation setups. Some of them, with the examples of simulation experiments, are presented in the final part of this paper.

The work carried out aims at specification of a universal multi-agent system for modelling supply-chains and solving different aspects related to it. It seems that this goal was achieved to a high degree. The presented specifications contain a rather detailed description of the most important elements and pilot realisations prove the usefulness for solving different kinds of problems. Thus, the experiments have, in particular, shown:

- influence of modification of some parameters of a company on the results achieved by it, with consequences being in accordance with predictions,
- optimisation of the decision parameters of the company,
- analysis of influence of applying different strategies of stock management on the effects achieved by the company, and the influence of the changes of the state of the market (described by customer demand and preferences) on obtained results.

Our long-term intention is to describe the activities of a system and particular agents, as well as to prepare appropriate components in such a manner that it will be possible to build different systems adjusted to the specificity of given problems. The results obtained so far constitute a favourable prognostic, concerning the intended realisation of a system having a utilitarian value.

We are intending to focus on the analysis of the behaviour patterns, classification of these behaviours and learning so as to make a company able to efficiently adjust its strategy to the situation on the market.

Subsequent work on the approach is oriented at:

- taking into consideration long-term contracts; agents may negotiate contracts of delivering some amounts of goods with given time intervals; this should be accounted for in the stage of resource reservation; additionally, the company should decide, if it is willing to conclude long-term contracts and under what conditions.
- broader research on different methods of prediction of demand, supply and prices for given goods; this is associated with the choice of production and storage strategies.
- research on anomalies and critical situations; we are going to focus on patterns describing states being anomalies or leading to anomalies and critical situations, predict these situations, prevent them or minimise their consequences.

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