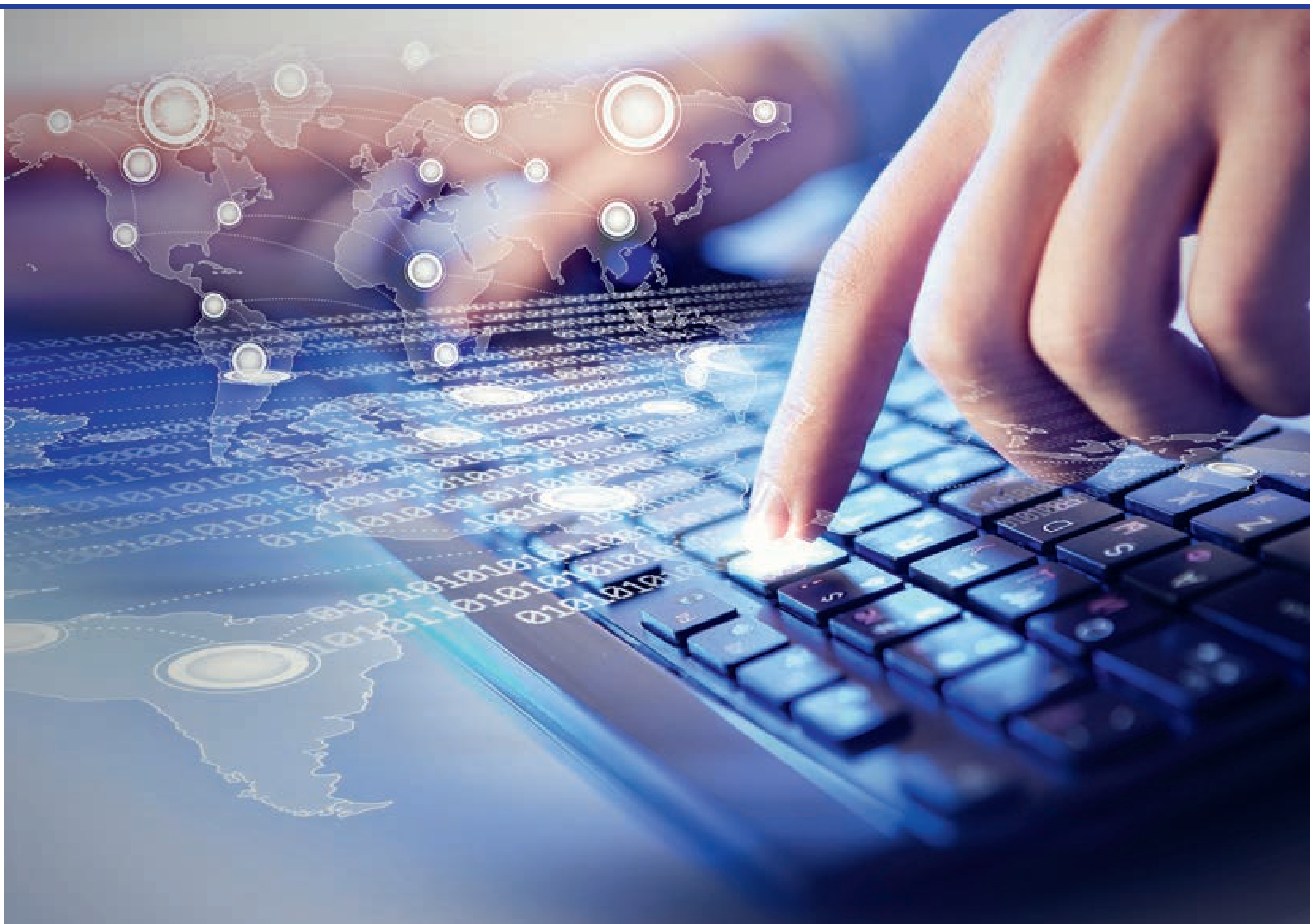
RIGA TECHNICAL UNIVERSITY

Darja Plinere

DEVELOPMENT OF A MULTI-AGENT SYSTEM FOR SUPPLY CHAIN MANAGEMENT EFFICIENCY IMPROVEMENT

Summary of the Doctoral Thesis



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Faculty of Computer Science and Information Technology

Institute of Information Technology

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DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR THE PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF SCIENCE

To be granted the scientific degree of Doctor of Science, the present Doctoral Thesis has been submitted for the defence at the open meeting of RTU Promotion Council on 15 December 2021 at 14:30 at the following link: https://rtucloud1.zoom.us/j/94856558679

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Science is my own. I confirm that this Doctoral Thesis had not been submitted to any other university for the promotion to a scientific degree.

Darja Plinere ……………………………. (signature)

Date: ………………………

The Doctoral Thesis has been written in Latvian. It consists of Introduction; 5 chapters; Conclusion; 65 figures; 50 tables; 4 appendices; the total number of pages is 161, including 4 appendices. The Bibliography contains 105 titles.

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GENERAL CHARACTERISTICS OF THE WORK

Topicality

Academic and industry research in supply chain management is still ongoing today. Some studies are devoted to developing a new strategy that could increase profits or reduce costs; while others are trying to create a new direction in supply chain management. The aim of all these studies is to improve the existing supply chain and its efficiency.

Today, only some companies conduct research to improve supply chain management, apply the results and reap the benefits. Changes in their supply chain management do not change or affect other participants in the supply chain. Improving supply chain management, which can connect different participants in the supply chain and improve common and separate performance indicators, remains a challenge.

In today's dynamically changing environment, we need to be able to respond in a timely manner to changes in supply chain processes. Software agent(s) are successfully used in supply chain management tasks for a variety of purposes. The behaviour of agents is determined by the purpose of their development, and the effectiveness of the use of agents is considered in accordance with the purpose of their development. If the number of agents is more than one, the mode of communication between the agents should be defined during development.

Despite the availability of multi-agent systems [28], [29], [37], [77], [100], the problem of using agents to improve the efficiency of supply chain management is still relevant. The system to be developed must be adaptable to different applications and be able to complement existing systems.

In the Thesis, a research on the development of a multi-agent system for improving the efficiency of supply chain management, which can be applied by various participants in the supply chain, has been carried out focusing on the steps of developing a multi-agent system. One of the first steps should be to define the quantity of agents and ability to add new agents if the need arises in the future, as well as to analyse the way the agents communicate with each other: through a blackboard system, ontology or communication via the environment. In the Thesis, a research on possible ways of communication has been carried out, paying major attention to the development of ontology and its validation.

The Thesis also includes a research-based list of supply chain efficiency indicators which tests the efficiency of application.

Research aim and tasks

The aim of the Thesis is to develop an approach to the development of a multi-agent system that ensures the improvement of supply chain management efficiency. In order to achieve the aim, the following tasks have been formulated:

1. Analyse and select supply chain management efficiency indicators that cover supply chain tasks for system efficiency evaluation.
2. Study multi-agent systems, their application in supply chain management and reuse.

3. Develop a multi-agent system architecture suitable for each node of the supply chain, ensuring the improvement of supply chain management efficiency.
4. Create a reusable multi-agent system and test it on real company data.
5. Experimentally prove the efficiency of the application of the developed multi-agent system using the selected supply chain efficiency indicators.

Research hypotheses

The following hypotheses were put forward during the development of the multi-agent system development approach:

1) The information sharing in multi-agent systems is able to speed up the operation of a multi-agent system by using another agent information necessary for the operation or its results.
2) The application of ontology ensures the re-use of a multi-agent system by creating a multi-agent system template for supply chain management.

Research object and field

The object of the research is the system of improving the efficiency indicators of supply chain management.

The subject of the research is a multi-agent system with ontologies and information sharing.

Research methodology

Software agents were used in the Thesis. It is proposed to represent each node in the supply chain with the same set of agents. Agent behaviour is determined by supply chain activities, offering improvements in supply chain management efficiency. Several methods of improving the efficiency of supply chain management were used in the Thesis, for example:

- inventory management,
- production planning.

In order to improve the inventory management, the agent processes available information from previous periods and uses ABC analysis and forecasting algorithms for future orders, as well as replenishment policies. In order to improve production, it is proposed to use a production scheduling, that is, a production sequence that reduces the total production time, thus reducing production costs. Communication between supply chain nodes is implemented using ontologies. Cooperation between agents in a single node is initiated through data and knowledge sharing, similar to blackboard systems.

Scientific novelty

The scientific achievements and novelty of the Thesis are based on the analysis of existing methods and proposals for innovations. The scientific novelty and main achievements are as follows.

1) The developed approach to multi-agent system development that allows it to be applied to different participants in the supply chain and ensures the improvement of supply chain management efficiency provides:
   - multi-agent system re-use using the developed interface for description of production processes;
   - supply chain management efficiency improvement through the developed agents that include algorithms for improving system performance.
2) The proposed hybrid way of agents communication – information sharing between same-node agents, thus reducing the need for communication, and using an ontology for inter-node agent interaction.

Other results achieved during the development of the research are:

- supply chain management efficiency indicators were investigated,
- agent communication tools were examined,
- existing ontology validation methods were analysed,
- agent performance algorithms were proposed in order to improve the efficiency of supply chain management.

Practical significance

Practical significance of the Thesis – application of the developed multi-agent system to various participants of the supply chain, which is ensured by the developed approach allowing to implement re-use and efficiency improvement by using

- inventory management, thus reducing inventories and related storage costs;
- production planning and re-planning, which helps to define efficient production time and allows to reduce the total production time, thus reducing production costs;
- inter-node communication, which speeds up inter-node interaction and ensures continuous operation.

Approbation

The results of The thesis were reported at **14 international scientific conferences**, receiving positive evaluation:

1. IEEE Workshop "The 7th IEEE Workshop on Advances in Information, Electronic and Electrical Engineering AIEEE'2019" (Latvia, 2019)
2. The 58th International Scientific Conference of RTU (Latvia, 2017)
3. The 57th International Scientific Conference of RTU (Latvia, 2016)
4. The 56th International Scientific Conference of RTU (Latvia, 2015)

5. The 8th International Conference on Soft Computing, Computing with Words and Perceptions in System Analysis, Decision and Control (Turkey, 2015)
6. The 55th International Scientific Conference of RTU (Latvia, 2014)
7. The 52nd International Scientific Conference of RTU (Latvia, 2011)
8. The 15th International Conference on Soft Computing, MENDEL'09 (Czech Republic, 2009)
9. The 50th International Scientific Conference of RTU (Latvia, 2009)
10. The 49th International Scientific Conference of RTU (Latvia, 2008)
11. The 14th International Conference on Soft Computing, MENDEL'08 (Czech Republic, 2008)
12. Estonian Winter School in Computer Science (Estonia, 2008)
13. The 48th International Scientific Conference of RTU (Latvia, 2007)
14. The 47th International Scientific Conference of RTU (Latvia, 2006)

The basic results of the Thesis have been published in **18 scientific publications**, which were cited 90 times:

1. Plinere, D., Aleksejeva, L., Merkuryev, Y. Multi-agent system development and application for supply chain management tasks. *Information Technology and Management Science*. 2021 (in press).
2. Plinere, D., Merkuryev, Y. Designing A Multi-Agent System For Improving Supply Chain Performance. In: A. Romanovs, D. Navakauskas, A.Senfelds (eds*.) Advances in Information, Electronic and Electrical Engineering (AIEEE): Proceedings of the 7th IEEE Workshop,* Liepaja, Latvia, 15–16 November, 2019. IEEE, 2019, pp. 62–68. Indexed in: Scopus. Cited: 2.
3. Plinere, D., Aleksejeva, L. Production Scheduling in Agent-based Supply Chain for Manufacturing Efficiency Improvement. *Procedia Computer Science*. 2019, vol. 149, pp. 36–43. (ICTE in Transportation and Logistics 2018). Indexed in: Scopus, Web of Science. Cited: 8.
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5. Plinere, D., Aleksejeva, L. Agent System Application as a Tool for Inventory Management Improvement. In: *Proceedings of Eighth International Conference on Soft Computing, Computing with Words and Perceptions in System Analysis, Decision and Control (ICSCCW-2015),* Turkey, Antalya, 3−4 September, 2015. b- Quadrat Verlag, 2015, pp. 157−166. Cited: 2.
6. Plinere, D., Borisov, A., Aleksejeva, L. Взаимодействие программных агентов в задаче согласования заказов. *Автоматика и вычислительная техника*. 2015, т. 49, № 5, c. 23−34. ISSN 0132-4160. Indexed in: Scopus, Web of Science, SpringerLink.

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11. Plinere, D., Borisov, A. A Negotiation-Based Multi-Agent System for Supply Chain Management. *Information Technology and Management Science.* 2011, vol. 49, pp. 128−132. Cited: 3.
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13. Plinere, D., Borisov, A. Ontology-Based Knowledge Acquisition System for Product Life Cycle Task. In: *Mendel 2009: Proceedings of 15th International Conference on Soft Computing*, Czech Republic, Brno, 24−26 June, 2009. Brno: Brno University of Technology, 2009, pp. 292−297. Indexed in: Scopus.
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During the development of the Thesis, the author participated in the following scientific projects:

1) Strengthening of the academic staff of Riga Technical University in the fields of strategic specialization (RTU PVS ID 3826, C3826.8.1.) (17.04.2020-16.04.2021)

2) LZP grant No. 051639, "Intelligent computer technologies for poorly formalized decision-making tasks". Chairman Prof. A. Borisovs (2005−2008)
3) IZM – RTU research project R 7391 "Convergence of information in distributed intelligent systems". Chairman Leading Researcher A. Vališevskis (1.03.2008. − 31.12.2008.).

Structure and content of the Thesis

The Thesis consists of an introduction, five chapters, analysis of the results and conclusions, bibliography and appendices. The text of the Thesis is presented on 161 pages and is supplemented with 65 figures and 50 tables. The bibliography list contains 105 titles. The structure of the Thesis is as follows.

Chapter 1 is devoted to supply chain definitions, processes and tasks. Various opportunities to improve the functioning of the supply chain, their advantages and disadvantages are covered. As a result, the development of a multi-agent system is proposed to meet the requirements of the research. At the end of this chapter, the supply chain performance indicators and their metrics are described and analysed, according to which the efficiency of the developed multi-agent system will be evaluated.

Chapter 2 investigates agents and multi-agent systems, and types of agent interactions. Existing multi-agent systems are analysed and evaluated. The development of the JADE agent is described at the end of this chapter.

Chapter 3 describes the development of the approach to multi-agent system development. It covers major development steps, including multi-agent system architecture, and agent behaviour algorithms.

Chapter 4 is devoted to the progression of the developed multi-agent system. The chapter describes the situation when there is a need to apply new agents in the system and / or include new indicators in the developed multi-agent system. At the end of the chapter, the situation is discussed when one of the agents is not needed and has to be removed from the system.

Chapter 5 shows the application of the multi-agent system, an analysis of real company data and the improvement of supply chain management processes. At the end of this chapter, supply chain performance analysis and multi-agent system efficiency evaluation are provided.

The **concluding chapter** discusses the implementation of the tasks stated, analyses the results achieved, as well as provides general conclusions on the system and future work.

SUMMARY OF THESIS CHAPTERS

1. SUPPLY CHAIN MANAGEMENT AND METHODS FOR IMPROVING ITS EFFICIENCY

The chapter discusses supply chain definitions, the range of supply chain tasks, and the basics of supply chain management. Existing supply chain performance improvement technologies are analysed, and a detailed overview of existing multi-agent systems for supply chain management is offered. At the end of the chapter, the requirements for the development of a multi-agent system are determined and the supply chain performance measurement and its metrics are defined.

Supply chain management basics and key concepts

A **supply chain** is a set of nodes in a logistics system that is linearly arranged with product, information and financial flows to analyse specific logistics functions and / or costs. The products flow involves the movement of goods mainly from the supplier to the buyer; in the case of the return of goods, this flow changes direction. The information flow includes sending orders and updating delivery status. Financial flow consists of credit terms, payment schedules and ownership agreements. The supply chain reflects the production path, from the purchase of raw materials, their transformation into finished products and their delivery to final consumers. This path passes through raw material suppliers, manufacturers, logistics centres, warehouses, transport companies, wholesalers, retailers, and others [48].

Supply chain management, in turn, is a discipline that focuses on the integration of suppliers, factories, warehouses, distribution centres, and retailers to produce and distribute goods to the right customers, at the right time, in the right place, and at the right price. In addition, in a way that reduces costs while providing a certain level of service [82].

Supply chain management involves the following stages: planning, purchasing, production, delivery and return [102]. Each stage has tasks [93] that are worth looking at separately.

The task of the **planning phase** is to manage all the resources that are used to meet customer demand. This is the strategic decision-making level. Part of the planning phase is the development of a set of indicators or key performance indicators in order to monitor the performance of the supply chain so that it is efficient, reduces costs and provides high quality and value to customers.

The task of the **procurement stage** is to select the suppliers who will deliver the raw materials or services needed to produce the product or provide the service. A set of prices, delivery and payment processes with suppliers needs to be established, and metrics need to be established to monitor and improve the relationship.

The **production phase** includes production planning; its task is to plan the activities required for production, inspection, packaging and preparation for delivery. At this stage, quality levels, output and employee productivity need to be assessed.

The task of the **delivery phase** is to coordinate the receipt of orders from customers, to develop the warehouse network, to choose carriers for customers to receive the goods, and to create an invoicing system for receiving payments.

The **return phase** involves the task of networking to receive discarded and redundant products from customers and to support customers who have problems with the goods delivered.

The above tasks formulate the main supply chain management processes, namely: purchase of raw materials, production planning, packaging and delivery of finished products, coordination of payments with suppliers and customers, and the creation of a route for returned products.

In the planning phase, delivery, use of services, production, demand forecasting and safety stocks must be planned. A set of indicators or key performance indicators that take place during the planning phase needs to be developed in order to monitor supply chain performance.

In ***supply planning***, a company can change its product offering by managing a combination of two factors, and these factors are production capacity and inventory.

When ***planning the use of services***, the company must decide whether to use one supplier or several. Multiple suppliers ensure some competition and reduce the risk if one supplier fails to supply raw materials.

Information technology is used in ***production planning***, mainly in general planning in the supply chain. Nowadays, planning modules can consist of a nonlinear optimization package, because not all reasonable objective functions or constraints are linear functions. In any case, linear programming is usually the best way to solve problems [17].

Demand forecasting planning is the basis of supply chain planning. The first step that needs to be taken is to anticipate what the customer demand will be. Past demand, lead time, planned advertising or marketing activities, planned price discounts, economic situation, as well as the actions taken by participants affect the forecasting of demand. There are four types of forecasting methods – qualitative, time series, causality, and modeling forecasting methods [17].

The task of ***safety stock planning*** is to determine the level of stocks that would meet demand with lower storage costs. Stocks are a key issue for products with a short product life cycle, as these products can become worthless. The level of safety stocks is determined by two factors: the uncertainty of demand and supply, and the desired level of product availability. If uncertainty increases, the required level of safety stocks will increase. Increasing the level of availability of the desired products also increases the required level of safety stocks.

Analysis of existing supply chain management performance improvement technologies

The analysis showed that the studies researching the ways to improve the supply chain management performance could be divided into four groups:

- the first group [46], [96] studied the facility location task;
- the second group [83], [88] suggested the use of simulation modelling software;
- the third group [31], [41], [52] used the LEAN production process;
- the fourth group of authors [28], [29], [37], [77], [100] suggested the use of agents for supply chain management.

All of these researchers have achieved their goals, and these research directions can be successfully applied, according to the specific task:

1) Facility location is a task of strategic planning; it is mainly necessary in the strategic planning stage of the supply chain. It addresses the following issues: where to build or

lease a factory or a warehouse, to determine their quantity for the optimal operation of the company, how to determine the location of equipment and its capacity. In case of an existing supply chain, the challenge could be to open the next building or buy equipment to meet greater customer demand.

2) The advantage of using a simulation modelling tool is to apply different strategies and determine the best strategy or better configuration of the supply chain.
3) The LEAN methodology can ensure continuous operational improvement by eliminating redundant and non-value-adding activities in the supply chain.
4) A multi-agent system can offer improved supply chain management by allocating tasks to agents, and they will work together to achieve better system performance results [62].

Analysing the above research directions, it was concluded that multi-agent systems are the most suitable for improving supply chain management performance, as they are able to offer continuous improvement in dynamically changing conditions, include other improvement methods, and be successfully applied in both existing and new companies.

Overview of existing multi-agent systems and multi-agent system requirements for supply chain management

Multi-agent systems are used in various problem areas, such as health care [3], [32], [80], education [7], [23], [50], and others, but only multi-agent systems for supply chain management were analysed in the Thesis. Five works were selected [28], [29], [37], [77], [100], which address similar issues as the doctoral Thesis but do not solve the specific tasks.

The analysis concluded that the existing multi-agent systems are not suitable for re-use, as they are designed for specific tasks; therefore, the following multi-agent system requirements were set to improve supply chain management:

1) Ability to work with real world data.
2) Ability to forecast a demand.
3) Production planning and re-planning.
4) Ability to communicate with suppliers and customers.
5) Application of inventory management methodology.
6) Information sharing between agents of one company.
7) Multi-agents system re-use.

Therefore, it is necessary to create a distributed multi-agent system that offers the performance of supply chain functions in a way that increases overall performance. Supply chain processes are divided into several agents; these agents can operate in parallel, thus reducing performance time. The developed system should ensure the sharing of information between agents, thus reducing execution time and avoiding unnecessary communication between agents.

Performance measurement and its indicators for the developed system

Effective supply chain management is planned and targeted. A value-oriented supply chain that is in line with a company's strategic priorities is the result of deliberate management action and strategic investment [45].

The most common indicator of supply chain performance are [27]: order fulfillment time – time from an order receipt to a delivery of ordered goods; quality of goods and products; capacity utilization; planning method; customer service level; delivery on time; customer request processing time and inventory costs.

According to multi-agent system requirements, the performance indicators of the supply chain management system to be developed are described in Table 1.1 As the aim of this study is to provide a system that performs supply chain functions by providing performance improvements, performance indicators reflect the purpose of the study. The benefits of the developed system can be calculated using these indicators. Achieving the target values of these indicators drives the system to the achievement of the ideal system performance.

Table 1.1

Supply Chain Performance Indicators and their Criteria

#	**Supply chain performance indicators**	**Criteria**
1	Total production time	Reduction of total production time
2	Inventory storage costs	Reduction of inventories without shortages
3	Customer request processing time	Reduction of request processing time
4	Service level	The achieved desired service level

The developed system does not need to provide modifications to sales strategies, so changes in sales volume will not be taken into account. An indicator such as on-time delivery will also not be taken into account, as the delivery of products is often carried out by another company; production ends with the packaging of the products and their placing in the warehouse.

Conclusions of Chapter 1

Based on the results of analysis and research, the main conclusions of the chapter were drawn. First, there are different methods to improve supply chain management performance, each of which is effective in specific cases. Second, the existing multi-agent systems are designed for individual tasks or companies and cannot be reused. Third, the development of a reusable multi-agent system is able to offer a single system for supply chain participants.

The next step to achieve the goal of the Thesis is to study the multi-agent system, its architecture and development.

2. FUNDAMENTALS OF THE MULTI-AGENT SYSTEM AND AGENT CHARACTERISTICS

The chapter describes artificial intelligence agents and multi-agent systems. At the beginning of the chapter, the definition and properties of an agent are discussed and the architectural classification of agents is given. The possibilities of agent interaction in multi-agent systems are explained in the middle of the chapter. The chapter describes in detail the blackboard system and ontology, as well as the advantages of their application. An overview of multi-agent system development platforms is given at the end of the chapter.

Agent definition and classification

The author proposes to summarize several definitions [43], [76], [97] and to consider that the definition of an agent is understood as follows: an **agent** is an autonomous and proactive computing system that interacts with its environment, responds in a timely manner to environmental changes, and can communicate and collaborate with other agents or users to achieve their goal.

Multi-agent systems are systems that consist of a number of interactive computing elements known as agents [97].

The advantages of using a multi-agent system are as follows: agents are dynamic, autonomous, able to interact with other agents and / or users and databases and servers, able to adapt to new conditions, able to learn, be proactive, can be mobile, independent, intellectual, goal-oriented, and reactive; multi-agent systems can split processes so that they run in parallel.

The author took two classifications of agents as the basis for developing the agent architecture [54], [76]:

- The agent classification includes eight agent types [54]: collaboration, interface, mobile, information, reactive, hybrid, smart and heterogeneous agent systems,
- Agent architecture can be classified by dividing agents into simple reflexive, model-based, goal-based, utility-based, and learning agents [76].

A heterogeneous system of agents and goal-based agents were chosen in this Thesis. Learning agents were not selected in this work, but there is an opportunity to apply them in further research.

Interactions between agents in a multi-agent system

The key feature of an agent is its ability to interact with its environment. The agent perceives its environment, uses what is perceived to select as an action, and then performs the action through its effectors [89].

In case of a multi-agent system, agents may need to interact with each other, and these types of interactions are as follows [100]:

- cooperation – action to achieve a common goal;
- coordination – organizing problem-solving activities to avoid harmful interactions or to use positive interactions;

- negotiation – reaching an agreement that is acceptable to all parties involved.

Agent interaction requires a certain type of communication. The author's analysis of existing multi-agent systems [62], [74], [102] revealed that existing multi-agent systems use a blackboard system [12], [19], [47], [57], [90] or ontology [4], [15], [29] for agent communication.

Multi-agent systems are suitable for areas where there is an interaction between different people or organizations with different and potentially conflicting goals and secret information. A supply chain is considered to be a set of intelligent agents, where each agent is responsible for one or more activities in the supply chain. The ontology, in turn, describes the subject area and becomes a mechanism to help understand and analyse the flow of information between agents. Using an ontology for a multi-agent system provides these advantages; an ontology allows knowledge to be structured and shared, increases the reliability of the multi-agent system, and provides a basis for interaction between agents [62].

Communication between agents in a multi-agent system can be achieved using a blackboard architecture. They do not communicate with each other, but use the blackboard as a central depository, place the data there, and the agents wait for the appropriate data to contribute. Agents work consistently; the blackboard is used as a central repository for all shared information. All the partial results of the agents are posted on the blackboard and used by other agents as soon as the final solution is found [74].

The author believes that the use of ontology for agent communication is the most promising way of communication and proposes to introduce information sharing in a multi-agent system similar to the blackboard architecture.

Analysis of agent development framework

There are several reviews and surveys on agent development frameworks and platforms [6], [9], [38], so the author proposes to analyse them according to the requirements. There are the following attributes to select a development framework with the desired value: price-free, performance-high, standard compatibility – *FIPA* (to work with other agents that meet the same standard), learning-convenient and high user support. The importance of the attributes is listed in descending order, which means that cost is the most important attribute in the selection of framework.

The most suitable framework is *JADE* – it is free, with high performance, *FIPA* compliant, high user support and easy to learn. The authors [6], [33], [37], [47] call *JADE* the most popular framework.

The author proposed to use *JADE* as a multi-agent system development framework for the supply chain management task in 2011 [62]. The main reasons were, firstly, prior knowledge of agents and the integration of agent communication in one platform [66], [67], [73], secondly, the easy way to learn agent construction in *JADE*, and thirdly, the visualization capabilities of agents.

Conclusions of Chapter 2

Based on the results of the analysis and research, the main conclusions of this chapter are as follows:

1. Agent communication can be implemented in two ways: blackboard system or ontology.
2. In future research agents with learning opportunities will be analyzed and used.

The author proposes to use an ontology for agent communication between supply chain nodes and to introduce information sharing for single node agents for initial data, partial and final results, as in a blackboard architecture.

The next task in developing the approach is to create a multi-agent system architecture that is appropriate for each node of the supply chain, ensuring the improvement of supply chain management efficiency.

3. DEVELOPMENT OF A MULTI-AGENT SYSTEM FOR SUPPLY CHAIN MANAGEMENT EFFICIENCY IMPROVEMENT

The chapter describes the development stages of a multi-agent system for supply chain management within *JADE*. At the beginning of the chapter, the developed approach for a multi-agent system creation is described. The development of a multi-agent system following this approach begins with a conceptual description of the multi-agent system and the determination of the number of agents. The architecture of the multi-agent system is described further – the means of agent behaviour and communication for inter-node communication are defined, as well as the development of information sharing for single-node agents. The development of the interface of the multi-agent system is shown at the end of this chapter. At the end of the chapter, the multi-agent system developed within the *JADE* framework and the limitations of the developed system are described.

Development of an approach for the multi-agent system creation

The development of the approach (Fig. 3.1.) ensures the creation of a multi-agent system for supply chain management so that it can be applied by different participants in the supply chain and to ensure the improvement of supply chain management efficiency. The following actions needed to be taken in order to develop the approach:

- To analyse and define supply chain participants and tasks to be solved.
- To describe the range of tasks in a supply chain.
- To study and determine the required number of agents for the respective set of tasks.
- To define and develop agent algorithms according to its functionality.
- To analyse and develop agents' means of communication.
- To study and develop the re-use of the multi-agent system.
- To create a multi-agent system architecture.

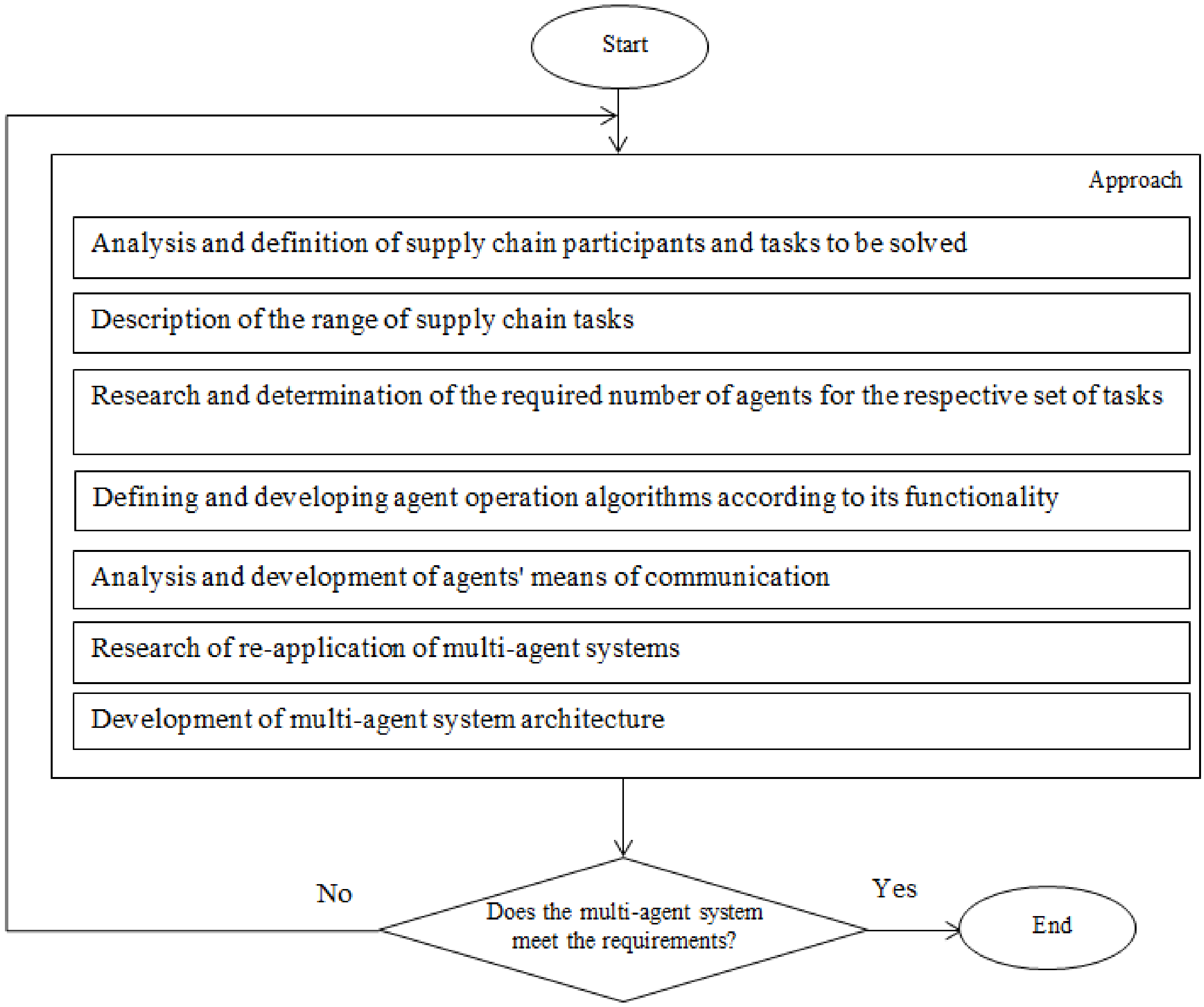

Fig. 3.1. The development of the approach.

According to the developed approach, a multi-agent system covering the set requirements was established; it was evaluated according to pre-defined efficiency indicators (Table 1.1).

Conceptual model of the developed multi-agent system

Following the developed approach, a multi-agent system was created, which can be used by all participants in the supply chain, but the Thesis demonstrates the operation of the system in detail in the manufacturer node because it includes production processes. The developed agents must be dynamic in order to work with dynamic data, autonomous and proactive for continuous analysis of the situation without waiting for a user intervention, purposeful – agent behaviour is goal-oriented, and intelligent for goal-based calculation. Communication between supply chain nodes is provided by two developed ontologies (Fig. 3.2.).

Within the Thesis, communication between agents in one node is considered on the example of the manufacturer node and is realized by sharing information, similarly as described in the blackboard system.

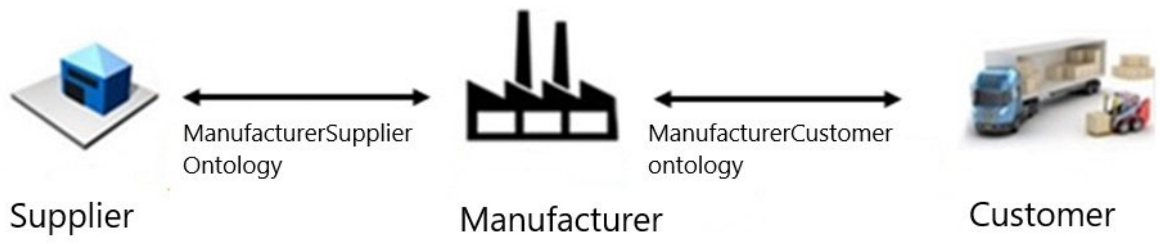

Fig. 3.2. Inter-node interaction through ontologies.

The development of a user interface that describes the production processes for a multi-agent system and the developed agent behaviours, which do not depend on the data of each individual case, ensures the re-use of the created multi-agent system. A multi-agent system can be reused by other participants in the supply chain and it contains the following elements: a user interface for an individual description of the production process, *n* agents, the number of which will be discussed further, two ontologies for communication between nodes and information sharing implementation.

Describing the production processes in the user interface and adding the data that is necessary for the activities of the agents creates an individual implementation of the multi-agent system (Fig. 3.3.).

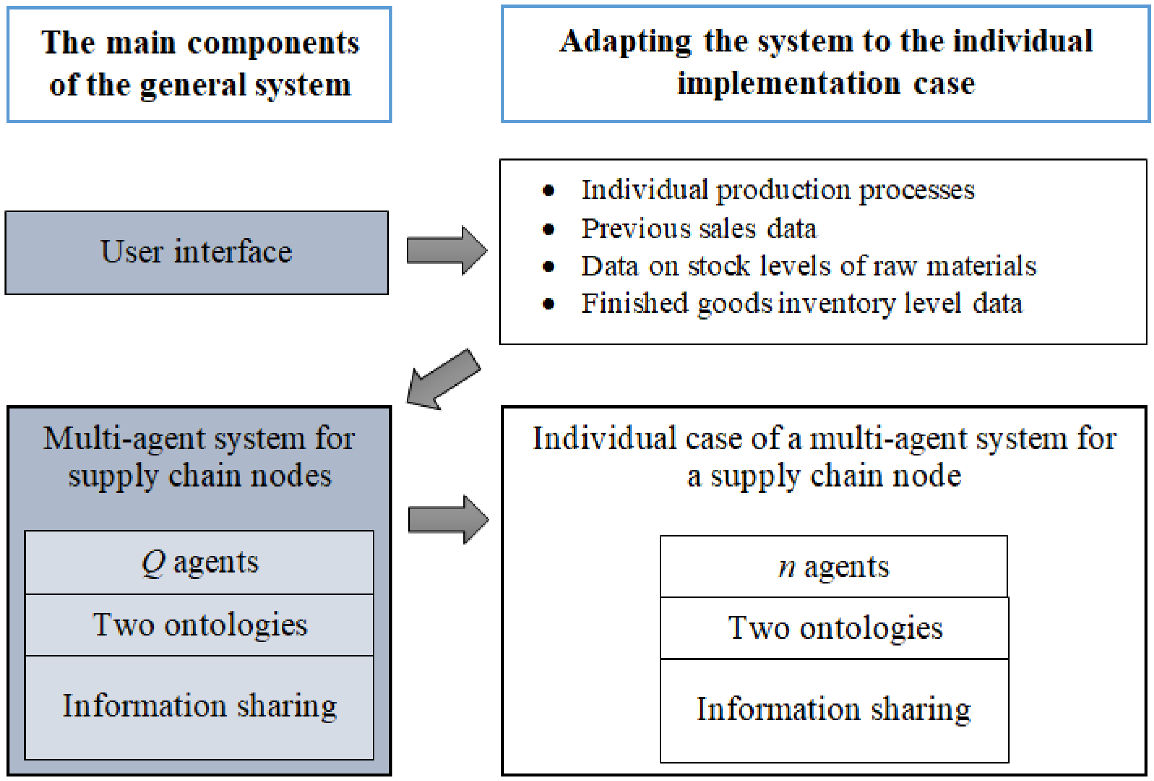

Fig. 3.3. Description of the development of a new case of a multi-agent system.

Given the proposed approach to developing a multi-agent system, it is, first, necessary to define the number of agents in the manufacturer node and their behaviour.

Supply chain functions must be shared between agents in the way they exist in nature; furthermore, each agent must be reconfigurable without modifying the entire system. The agent must reflect in a general way one of the functions of the supply chain, such as purchase, production or sale. These three agents can represent the manufacturer node, but within the framework of the Thesis it is proposed to improve the supply chain performance indicators; therefore, the developed multi-agent system should also include inventory management.

Supply chain management functions are divided into four agents shown in Table 3.1 These functions exist at each node in the supply chain, so each node can be represented by similar agents. The production function can be in other supply chain nodes, not only in Manufacturer node, for example, creating a set of purchased tables and chairs in a Distributor node.

Table 3.1

Division of Supply Chain Functions into Agents

#	**Supply chain functions**	**Name of agent**
1	Purchase	Procurement agent
2	Production	Assembling agent
3	Sale	Seller agent
4	Inventory management	Inventory management agent

In order to include the communication function between the supply chain nodes, it is proposed to create two more Supplier and Distributor / Customer company agents – the Supplier Agent and the Customer Agent, where communication between the nodes is demonstrated with the help of arrows (Fig. 3.4.). The aims and behaviours of these two agents are similar to the manufacturer's Seller agent and Purchasing agent, respectively.

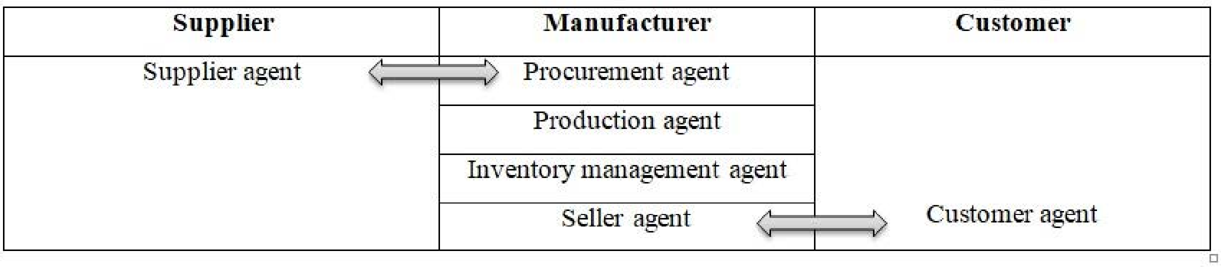

Fig. 3.4. Agents of the developed multi-agent system.

Seller agent development

It is assumed that the Seller agent has no information on future customer demand or it has limited information on customer demand, although the exchange of information on demand can benefit all participants in the supply chain.

The following behaviour of the Seller agent is offered in the developed multi-agent system: the agent is responsible *for receiving orders from customers*, it interacts with buyers on delivery time. The price of the product is fixed, the agent cannot change it.

Initially, the Seller agent is idle; it is activated when a new order is received from the Customer agent. The rules of Seller agent behaviour are as follows:

- If the ordered quantity is available in stock, reserve it and offer the Customer agent the price and delivery time.
- If the Customer agent accepts the price and delivery time, then start the sales procedure.
- If the Customer agent does not accept the price and delivery time, then cancel the reservation of the ordered products and stop the negotiations.
- If the stock level is less than the ordered quantity, then offer the Customer agent to wait a time equal to T where $T = T_{production}$ or $T = T_{production} + T_{purchasing}$, if the quantity of raw materials is not sufficient to assemble the ordered product.
- If the Customer agent refuses to wait for time T, then terminate the negotiations.
- If the Customer agent agrees to the waiting time T, then continue negotiations until the Customer agent receives the ordered quantity.

Communication between the Seller Agent and the Customer agent is performed using the *ManufacturerCustomer* ontology. These agents have a common understanding of the information they are talking about .

Assembling agent development

The capacity of the equipment, the sequence of production processes of the products and their execution times are defined by filling fields of the user interface. Within the Thesis, it is assumed that different types of products do not require reconfiguration of equipment and energy efficiency is not taken into account.

The developed multi-agent system offers the following behaviour of the Assembling agent: the agent is responsible for production planning and re-planning, for existing production orders, *plans the execution of new production orders* and *re-plans the production sequence*, if it is possible to reduce the production time.

The Assembling agent behaviour algorithm is as follows:

1) For n existing products, the different possible variants are $n!$ If it is necessary to produce five types of products, then $n! = 120$.
2) For each $n!$ variant, total production time must be calculated. A well-thought-out production sequence has the lowest total production time.
3) If the total production time exceeds the deadline, the production process priority level based on the results of the ABC analysis is used: the highest priority is for class A products, then for class B products, and the lowest priority is for class C products. If the products belong to the same class, then the priority of the production process is given to the product with a shorter production time.

This behaviour algorithm ensures efficient equipment load and reduces total production time, thus reducing production costs and eliminating unnecessary waiting time.

Inventory management agent development

It is assumed that the manufacturer does not have information on the future demand for the goods but has information on the previous demand. In order to reduce production stocks in the multi-agent system, it is proposed to use inventory management techniques.

The Inventory management agent has information about the quantity of raw materials and finished goods from the databases. Its main function is to make decisions about when and how much raw materials to buy and when and how much to produce. The agent has knowledge of the possible minimum stock level, i.e., the amount of security stocks for production capacity; moreover, the agent has a future demand forecasting algorithm. Inventory management agent uses the following methods: ABC analysis algorithm to determine management control, future demand forecasting algorithms for appropriate inventory control, and replenishment policy to avoid inventory shortage situations while reducing inventory levels [58], [62].

The essence of the proposed Inventory management agent behaviour algorithm is as follows: it dynamically manages the sufficiency of raw materials and finished products for production and sales. For each raw material and finished product, it calculates

- belonging to the ABC analysis class,
- demand forecast,
- safety stocks,
- ordering points.

After each new request, the demand is compared with the forecasted demand. According to the result, the agent recalculates the safety stock and the order point. Belonging to ABC analysis classes and demand forecast are recalculated, including new demand data.

ABC analysis is a basic supply chain management technique often performed by inventory / raw material managers and is the starting point for inventory control. ABC analysis is a categorization system; as a result of this analysis, inventories are classified into three classes, each with a different management control. The ABC analysis is based on the Pareto analysis, which states that 20 % of production represents 80 % of sales.

Demand forecasting in this context is forecasting or estimating the expected demand for products over a certain future period. There is a wide range of forecasting algorithms, and all of them can be analysed in the future, but within the Thesis the following forecasting methods were considered and included in the developed multi-agent system: Mean method, Naive method, Weighted moving average, and Exponential smoothing (1.1).

$$\hat{y}_{T+1|T} = \alpha y_T + \alpha(1-\alpha) y_{T-1} + \alpha(1-\alpha)^2 y_{T-2} + \cdots , \quad (1.1)$$

where α – smoothing parameter (0< α <1).

The Economic Order Quantity-Reorder Order Policy was chosen for the developed multi-agent system.

Procurement agent development

Within the Thesis, it is assumed that the supplier has the raw materials required by the manufacturer in unlimited quantities and they can be delivered without any delay. The Supplier agent and the Procurement agent (from the manufacturer) communicate using the *ManufacturerSupplier* ontology to understand equally their conversation.

The Procurement agent deals with the purchase of raw materials from suppliers. Initially, the Procurement agent is idle; when the quantity of raw materials reaches the order point, its operation is activated:

- send a request to the Supplier agent who supplies raw materials;
- if the price offered by the Supplier agent and the delivery time are acceptable, approve the offer; if not – reject it;
- when the ordered raw material is sent to the manufacturer, the Procurement agent enters the standby mode until the next situation with insufficient quantity of raw materials.

The Procurement agent is responsible for the selection of suppliers: with raw material minimal prices, the possibly highest quality and the fastest deliveries.

Development of ontologies

The exchange of knowledge between participants in the supply chain may face these barriers: confidentiality, trust, and standards [78]. In turn, the Thesis offers information sharing as a means for information exchange and processing between agents from the same node and ontology for inter-node communication, using the same description of information in a formal way.

The developed system has two different ontologies for inter-node supply chain interaction: *ManufacturerSupplier* ontology and *ManufacturerCustomer* ontology. They are used for agent communication within *JADE*.

The structure of the agent ontology is different from the usual ontology structure; it requires the abstract concept *AgentAction* and the abstract concept *Predicate*.

The author, inspired by the ontology evaluation approach based on the data source, proposes to create an ontology based on the description of the behaviour of Suppliers and Procurement agents for this task. In abstract terms, this can be described as follows: it is necessary to buy raw materials *RM* in quantity *Q* at the possibly lowest price and the shortest lead time; this request must be numbered. This behaviour can be demonstrated by ontological concepts for Supplier and Manufacturer communication: *RawMaterials* with subclasses *RawMaterial1*, *RawMaterial2*. The concept of *AgentAction* is *Buy*, which describes the purpose of the agent conversation. The predicate concept is *Costs*, which describes the price of a raw material price, where the price is a slot with a float value type. There is also a need for concept *Documents* with a subclass of *Invoice*. The development of the *ManufacturerCustomer* ontology is similar to the *ManufacturerSupplier* ontology due to the tasks they perform (Fig. 3.5.).

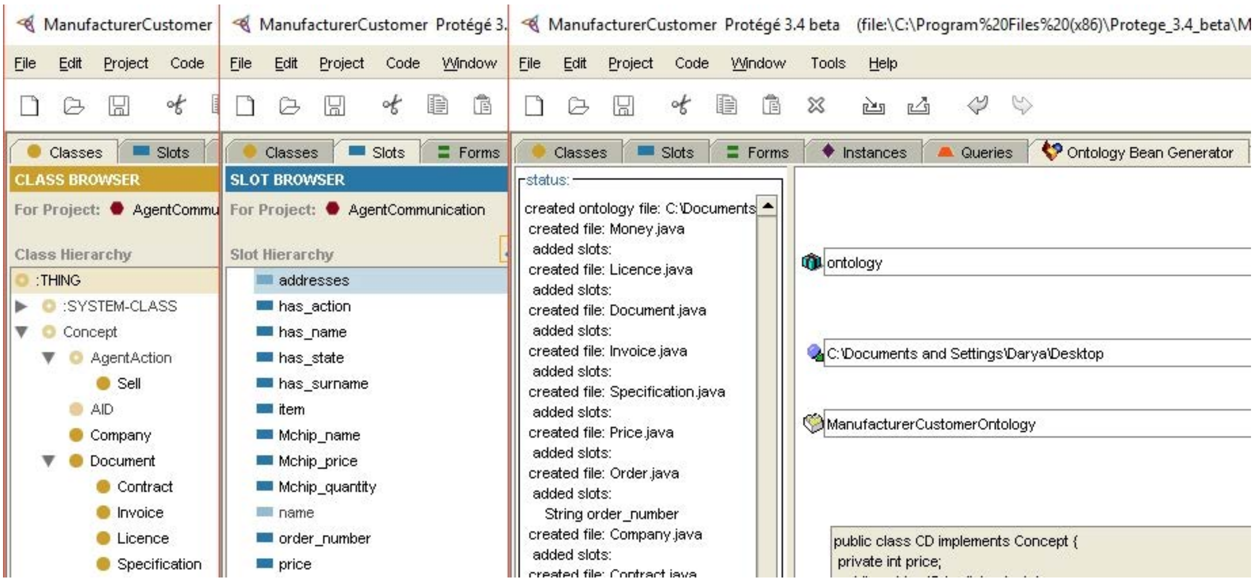

Fig. 3.5. Development of a *ManufacturerCustomer* ontology for use within JADE.

The author proposes to use an application-based evaluation approach for this ontology.

Development of the interface for entering initial data for the multi-agent system

At the beginning of the research, while developing a multi-agent system, where the interaction between agents, including that between agents of the same node, was realised with ontologies; the ontology of the production node summarised agent behaviours, tasks to be solved, and causes of agent communication. This ontology included all the information about each agent to achieve its goal and tasks.

The procurement process is as described above; during the communication with suppliers, the Procurement agent draws up its ‘list’ of suppliers in the manufacturer ontology. This list contains the name of the company, the ordered raw materials and their quantity, as well as the delivery time of each order. The minimum and maximum execution time from each company is calculated. This can help in deciding on a supplier in the case of time constraints.

The Inventory management agent has the following data: priority level of products to be produced, forecasting results, and replenishment policy.

For the activity of the Assembling agent, the following information must be provided: the capacity of the production equipment, a description of the production processes, the time of the production process and the quantities of raw materials required for the production of the finished product.

The Seller agent compiles a list similar to the one of the Procurement agent, which includes customers, purchased goods, service level, priority level and manufacturers satisfaction with their cooperation.

As a result of this research, the development of the ontology led to the idea of developing an *ontology-based interface* for entering initial data into a multi-agent system, considering each situation as a new case of ontology and creating a manufacturer ontology.

Agent actions are defined in the behaviour of each agent in a multi-agent system; all agent activities, except manufacturing, are identical for different system applications. The production process is a feature of the specific application.

The description of the production process allowed concluding that each individual case can be an individual of the production ontology, and the agents will use the added information in their activities.

The description of the production process includes the sequence of production operations and the processing times of the production batch. The names and quantities of raw materials are necessary to produce the finished product according to its production technology. This case-by-case description of the individual production technology formulates a lower-level ontology, while the upper-level ontology formulates the production ontology of production area for further reuse. The domain ontology can be displayed in the following user interface (Fig. 3.6.).

This individual case provides the Manufacturing agent with the data necessary for its operation. The addition of a raw material database, a finished product database and historical sales data create a multi-agent system with specific data.

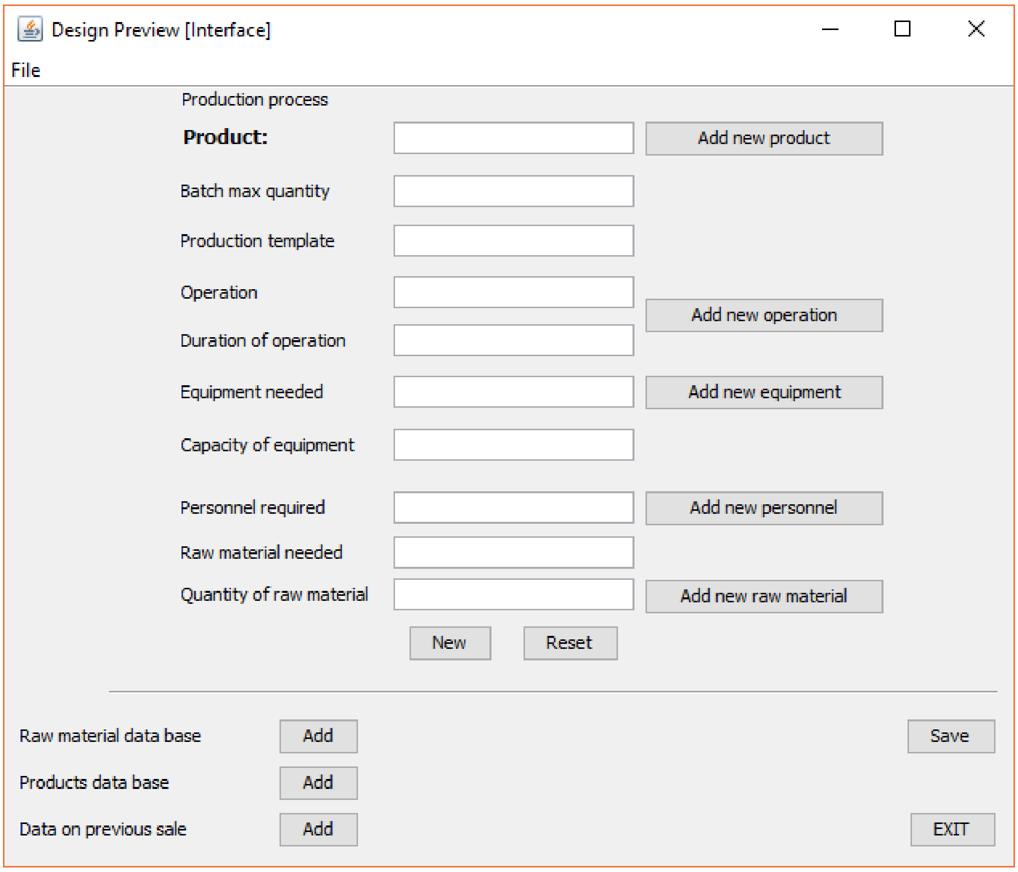

Fig. 3.6. Domain ontology representation in the user interface.

Development of multi-agent system architecture

The developed multi-agent system can be used by different companies tasked with purchasing different raw materials or products, possibly converting them into finished products and reselling, while trying to reduce storage and production / conversion costs.

Integration requirements are applied to the operation of the developed system:

- The use of an Assembling agent requires a description of the production process – the sequence of processes, the required raw materials, production time, production equipment capacity, etc.; this information is entered in the user interface.
- Procurement behaviour requires access to the raw materials database / inventories.
- The behaviour of the Inventory management agent requires data from previous period requests.
- The Inventory management agent and Seller agent must provide access to the finished goods database / inventories.

The reusable multi-agent system developed according to the proposed approach is shown in Fig. 3.7. It consists of six agents, four of which are manufacturers' agents, the fifth agent represents the Supplier's Seller agent (Supplier agent) and is designed as the Seller agent, and the sixth agent represents the Customer's Procurement agent (Customer agent), this agent is designed as the Procurement agent.

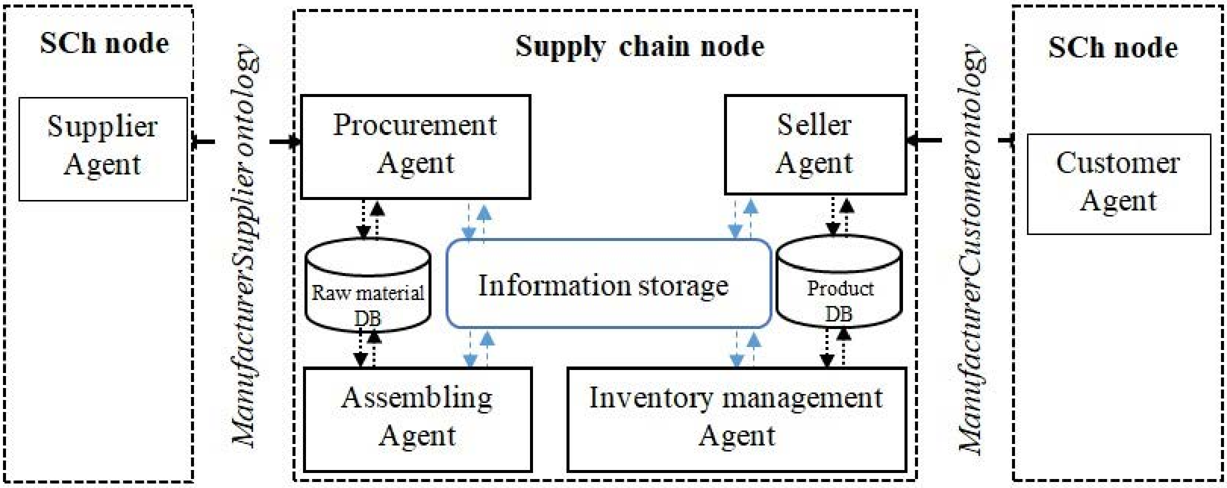

Fig. 3.7. The final appearance of the developed multi-agent system.

The application of the developed multi-agent system begins with the completion of the user interface and then the individual execution of the multi-agent system within *JADE*.

Multi-agent system infrastructure and limitations

Java, *JADE* framework, *Protégé* ontology editor and its built-in *Ontology Bean Generator* module, *MySQL* database support, *Apache Ant* program code compilation and *NetBeans IDE* as an integrated development environment were used to create the developed multi-agent system.

The development of the multi-agent system provided for fault tolerance, which is aimed at continuous system availability, as well as the prevention of recovery time [99].

Conclusions of Chapter 3

1) The number of agents in a multi-agent system affects the efficiency of the system.
2) The developed interface for entering the initial data in the multi-agent system allows re-use of the developed multi-agent system, describing in each case the production processes with the required equipment and staff capacity, required raw materials and execution time for each production product operation;.
3) The developed multi-agent system can fulfill the functions of the supply chain, while offering to reduce inventories and improve production processes.

4. ADVANCEMENT OF THE DEVELOPED MULTI-AGENT SYSTEM

This chapter is devoted to the possibilities of advancement of the developed multi-agent system. If there is a need to advance the developed multi-agent system, for example, new efficiency indicators or new functionality, then this multi-agent system can be expanded. Conversely, if it is necessary to use a reduced amount of agents, for example, without production, then the developed multi-agent system can be reduced to the required agents. This chapter discusses the ways the multi-agent system can be advanced: firstly, by the development of a new agent, secondly, by adding a new efficiency indicator to the multi-agent system, and thirdly, through the reduction of the existing number of agents.

Introduction of a new agent in the multi-agent system

The developed multi-agent system reflects the basic functions of the supply chain; it was assumed that internal transportation is not included. However, it may be that the importance of this internal transport is quite crucial.

The goal of the Transportation agent is to reduce the transfer time by avoiding unnecessary and pointless activities. The task of the transportation agent is to offer the fastest, not the shortest, route from one equipment to another, while recording the transfer of parts and raw materials from the raw material warehouse to the production facilities and the transportation of finished products to the final product warehouse.

Initially, the Transportation agent is idle; when the Assembling agent creates a new production order, the Transportation agent records the amount of raw materials taken from the warehouse and continues its activity until the finished products are transported to the warehouse:

- Raw materials are taken from the warehouse for the execution of each order and the initial time is recorded.
- The Transportation agent knows the sequence of production operations and knows the location and destination; the Transportation agent calculates the fastest way to reach them.
- The start time of each stage of the production sequence is recorded, and when each stage of the production sequence is completed, the end time is recorded.

- In the last stage of production, the production time of the finished product is recorded, and the finished product is transported to the final product warehouse.

The Transportation agent does not need cooperation with other agents; it is run together with the Assembling agent. The developed multi-agent system (Fig. 3.3.) has five agents in each node.

Introduction of a new efficiency indicator in the multi-agent system

A new efficiency indicator could be energy efficiency, but with the addition of the Transportation agent, a productive production time is expected – the dependence of the net production time on the final production time (production time and transportation time).

After receiving the result, the overall efficiency of the equipment can be analysed. *Overall Equipment Efficiency (OEE*) is the gold standard for measuring production productivity. *OEE* is the ratio of the actual output obtained with an installation to the maximum power that can be expected from that installation during the same period. *OEE* is a standard metric used to measure production performance, with a broad view of all aspects of production. Using three factors, *OEE* provides the manufacturer with the best equipment utilization rate and helps focus on the improvements that most directly affect their profits.

Removing an agent from the multi-agent system

If one of the agents is not needed, it can be removed from the multi-agent system. For example, a multi-agent system is used by an intermediary who buys a product, changes the price and resells it. In this case, production and inventory management are not required.

Thus, the multi-agent system consists of two agents: Procurement and Seller agents; their activities in the multi-agent system require the data specified in Table 4.1.

Table 4.1

Multi-agent System Requirements

Agent	**Requirements**
Procurement agent	Access to the raw materials database
	List of suppliers
Seller agent	List of customers
	Access to the finished product database

However, if there is a need to improve the system with inventory management or in situations where warehouses are used, then inventory management, which is implemented with the help of the Inventory management agent, should also be used.

Description of the application of the developed multi-agent system

Before starting to use the multi-agent system, five steps of adapting the multi-agent system must be performed in each case, as described further.

1. Depending on the field of activity of the researched company, it is necessary to define the required amount of agents. This can be done by an employee of the company, following the procedure for determining the required amount of agents (see Fig. 4.1):
   - if the company is an intermediary, the following agents are required: Procurement agent for research and selection of suppliers, Seller agent for organizing the sales process and Inventory management agent for inventory reduction;
   - if the company carries out production or assembly, then an Assembling agent must also be used;
   - if the company has transportation and needs to find the fastest route from one place to another, then the Transportation agent must also be used.
2. The user interface is launched; if there is no production or assembly, access to raw material and finished product data and previous sales data must be added. Otherwise, it is necessary to enter a description of the individual case production process based on the proposed structure.
3. The next step is to execute *JADE*.
4. After launching the multi-agent system, the Inventory management agent takes the first step to define the current situation, set priorities, and analyse inventories.
5. The other agents then take action according to their goals and behaviours.

Conclusions of Chapter 4

1) The developed multi-agent system can be improved and advanced at any time as needed, instead of developing a new multi-agent system for each new application.
2) The multi-agent system may be upgraded with new functionality by adding a new agent or performance indicator, or vice versa: removing the agent from the multi-agent system if the need arises.

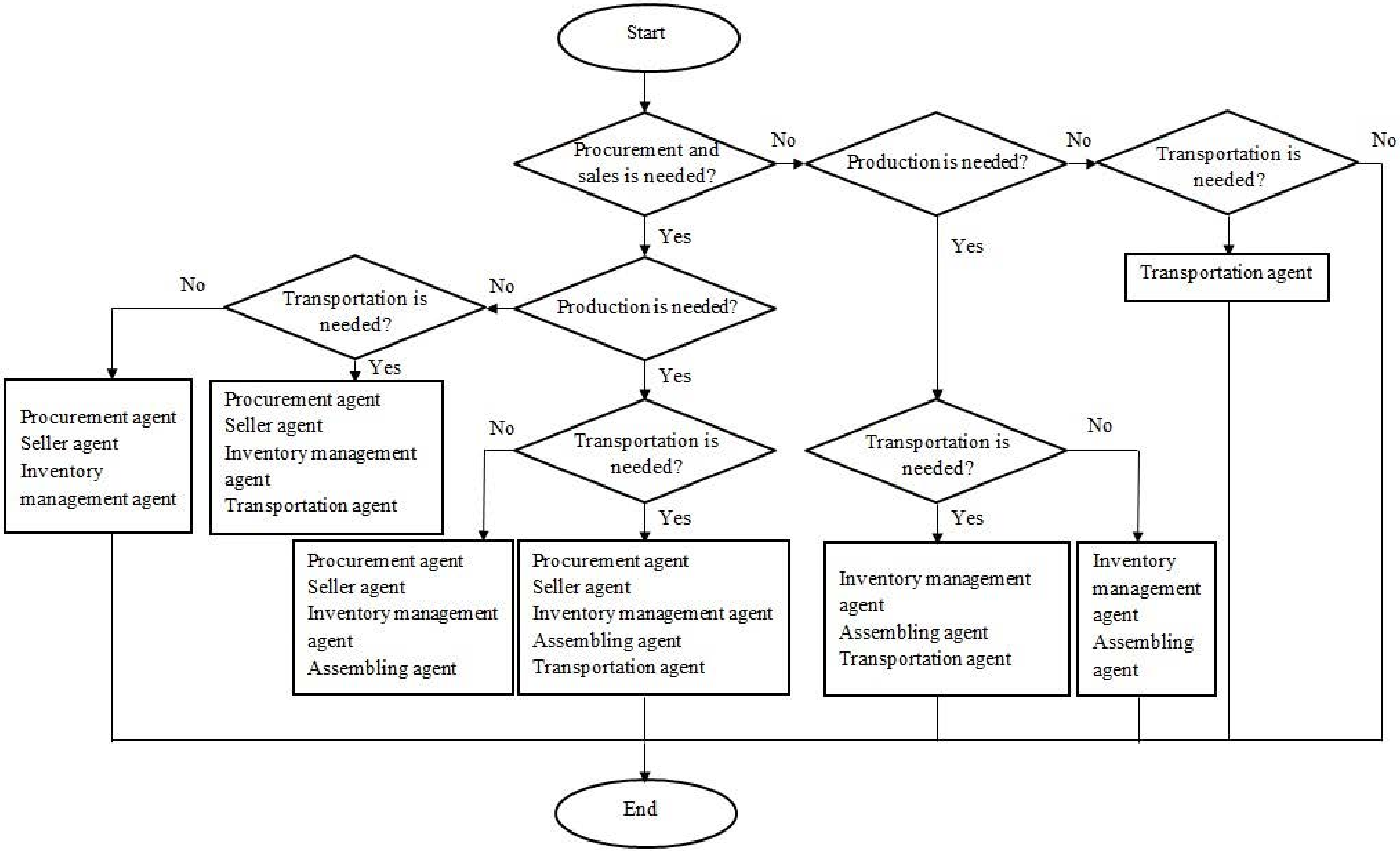

Fig. 4.1. The procedure for determining the required amount of agents.

5. APPLICATION OF THE DEVELOPED MULTI-AGENT SYSTEM

The chapter describes the application of the developed multi-agent system in supply chain management. At the beginning, the production company, its production specifics, available data and analysis of the existing situation in the company are examined. The following shows the creation of a multi-agent system according to the approach described. The chapter also looks at the activities of each individual agent, as well as their interactions and the application of the multi-agent system over a period of one to three months, analysing the results obtained and the results obtained for human activities. At the end of the chapter, the evaluation of the efficiency of the application of the multi-agent system according to the defined efficiency criteria is performed.

Approbation of the developed multi-agent system in a manufacturing company

The multi-agent system is applied in a manufacturing company that assembles chips and sells them. Data on the specifics of production and technology, as well as sales, purchasing and production volumes are available for this research.

The specifics of the production process are as follows: the chips are assembled using appropriate equipment and staff, all products can be divided into several groups according to the same production template. Each production mold uses the same equipment and personnel. This means that different types of chips can be expected in a queue to be produced in the same equipment. Therefore, one of the key issues is to find the production sequence to reduce the waiting time and the total production time.

At the beginning of the research, production took place in a production to warehouse mode, thus increasing inventories and their holding costs. Meanwhile, an order may also arise for products that are not available in the warehouse, such as new products or products that have not been in demand for a long time. The manufacturer's products are specific, so the buyer is ready to wait for his order, and the order preparation for delivery takes an average of one month. Production capacity does not allow timely production (on average one month) of all products in the required quantities, for example, on-demand production, so inventories are needed but must be managed and demand forecasting has to be included.

Production output with fixed sales in the research year is 56 pieces, the other 73 items are old products in stock and may never be redeemed due to old production data, or were produced for research purposes; while the amount of raw materials is 27 pieces.

Data for a 17-month period are available for the research; 14-month data are used for analysis, but data for the last 3 months are reserved for testing the performance of the developed system.

The production process is fully described and can be used to create a multi-agent system. The equipment required for production and the corresponding personnel are also described. Initial data on raw material quantities and stock levels of products should be included in the system. Data on past sales required for analysis are also provided and should be entered into the multi-agent system, as well as the above information.

The first step in the application of the developed approach is to determine the required agents. Going through the proposed procedure for determining the quantity of agents (Fig. 4.1), it was defined that the following agents are needed: Procurement, Inventory Management, Assembling, Seller, and Transportation agents.

The developed user interface allows entering the available information in the multi-agent system for further analysis and work with it. When the user interface is filled with data from the production process, the data on previous sales are in the appropriate form and the stock level of the finished product is initially connected to the system, then a multi-agent system is created.

Implementation of multi-agent system and its analysis

The first execution of the Inventory management agent in the ABC analysis revealed the following: 11 products (20 %) make 72 % of total profits. The first 20 % formulate class A and are the most critical. These goods require strict inventory control, frequent revisions of demand forecasts and utilization rates, very accurate batch data and frequent cycle tracking; the quantities of these products must be carefully controlled.

The next 30 % of the products make 15 % of sales revenue and belong to class B. These goods require mandatory stock controls, occasional revisions of demand forecasts and utilization rates, reasonably accurate data and less frequent but regular cycle counts; they should be closely monitored as they may become class A products.

Almost half of the production carries only 5 % of sales revenue and belongs to class C. These products have the least impact on warehouse performance and financial performance and, therefore, require minimal inventory control. The results of the ABC analysis are shown in Table 5.1.

Table 5.1

The First Results of the ABC Analysis after the Launch of the Multi-agent System (fragment)

Product	Sum, €	% from overall	Cum, %	Rank	ABC analysis result
MChip17	253392.65	17.27	17.27	1	A
MChip22	194404.77	13.25	30.52	2	A
MChip12	129759.02	8.84	39.36	3	A
MChip2	84182.60	5.74	45.1	4	A
MChip6	81483.58	5.55	50.65	5	A
MChip1	61195.88	4.17	54.82	6	A
...					
MChip37	37556.40	2.56	74.28	12	B
MChip43	37555.20	2.56	76.84	13	B
MChip21	35632.95	2,43	79.26	14	B
...					
MChip39	0	0	100.00	56	C

After ABC analysis, the Inventory management agent calculates the future product demand, safety stocks and reorder points. As can be seen from Table 5.2, there are two items that are lower than the order point and cannot meet the demand, which means they must be produced.

Table 5.2

Results of Demand Forecasting, Safety Stocks and Reorder Points for Class A Products

Product	Stock	Demand	Safety stocks	Reorder points
MChip17	10375	1397	1714	3111
MChip22	12406	100	4033	4133
MChip12	20722	9521	9840	19361
MChip2	5915	0	1299	1299
MChip6	5478	0	1642	1642
MChip1	69	194	228	422
MChip47	5671	9297	6388	15685
MChip14	7004	390	2692	3082
MChip53	753	7	692	699
MChip54	131	19	59	78
MChip38	581	480	929	1409

The inventory management agent found that two class A products could not meet the forecasted demand. Class A products represent the highest level of priority and should not be in short supply.

The plan of experiments

First, individual work of each agent and the application of multi-agent system were tested. The next goal is to test whether the results of using the developed multi-agent system will give better results than the operation of the existing company's system without it. The experimental plan for the developed multi-agent system includes:

3) processing of various customer requests;
4) choice between different suppliers;
5) operation of the multi-agent system during the first month and its analysis;
6) operation of the multi-agent system during the second month and its analysis;
7) operation of the multi-agent system during the third month and its analysis.

For this research, data of 14 months were used for analysis (demand forecasting, ABC analysis) but efficiency of multi-agent system application was tested for 3 months (the last 3 of the 17 months available for the research); human performance with the same initial data is known, multi-agent system efficiency should be tested.

The experimental plan also includes an additional experiment – the aim is to test the multi-agent system on the company's data, but for a shorter period of time – 9 months for analysis and 8 months for the performance analysis.

Processing of various customer requests

This experiment examines the simultaneous service of different buyers. A situation was considered when the production company received different requests at the same time. Different goods were ordered in this experiment of simultaneous service of different customers.

During the experiment, it was shown that the Seller agent is able to respond quickly to customer requests – the agent performs it in less than one minute, while the employee responds to the order up to one working day, depending on the employee workload during the request processing.

Choice between different suppliers

This experiment demonstrates the choice of the Procurement agent's supplier. If the required raw materials are available to several of them, then the best option should be chosen – the lowest price for raw materials and their delivery, with the same quality. Two suppliers were considered, with the same quality of raw materials but different purchase and delivery prices. The Procurement agent had to choose a supplier who would offer a better price at the same quality of raw materials.

Two situations were considered, where Supplier2 submitted a better offer and then Supplier1 offered more favourable conditions for the purchase of raw materials. In both cases, the best option for the manufacturing company was chosen; as different offers are expected, they are compared and the best alternative is chosen.

Operation of the multi-agent system during the first month and its analysis

The aim of the experiment is to numerically test the efficiency of the multi-agent system in comparison with human activity, working with the same initial data.

The first application of the multi-agent system begins with the initialization of an Inventory management agent to analyse available inventory and forecast future orders for developed production. The results of the ABC analysis can be seen in Table 5.1. The result of the Inventory management agent operation is demand forecasting, definition of safety stocks and order points.

Following the activities of the Inventory management agent and the results received, the Assembling agent is activated. The result of the Assembling agent performance and Seller agent performance – the demand is fulfilled, was demonstrated by the results of the first month. The results of the multi-agent system were compared with those of human activities (Table 5.3). The demand was fulfilled in both cases as a result of both the multi-agent system and human activities.

Table 5.3

Comparison of the Results of the First Month

	First month	
Stocks initial data	The result of multi-agent system	Human result
172403	**148413**	**155531**

The obtained results show that after the first month of operation of the multi-agent system, the amount stored in the warehouse has decreased in comparison with the effect of human activity, which, in turn, reduces the storage costs.

Operation of the multi-agent system during the second month and its analysis

The aim of the experiment is to test the performance of the multi-agent system after the second month of operation in comparison with the results of human activity. The results of the multi-agent system in the first month, i.e., the stock levels of the production, are used as the starting data for the second month.

The comparison of the second month multi-agent system performance with the human performance is shown in Table 5.4. The demand is met in both cases as a result of both the multi-agent system and human activity; the difference is at the level of stocks of finished products.

Table 5.4

Performance Results for Two Months

	First month		**Second month**	
Stocks initial data	The result of multi-agent system	Human result	The result of multi-agent system	Human result
172403	**148413**	**155531**	**135550**	**176903**

After two months, it can be concluded that the operation of the multi-agent system results in a reduction in stocks in the warehouse, while still meeting the demand of customers in a timely and full manner. In turn, during the second month, as a result of human activity, the warehouse inventory was increased compared to the results of the first month. Based on the obtained results, it can be concluded that the multi-agent system has better performance results.

Operation of the multi-agent system during the third month and its analysis

After the results obtained within two months in the company's production warehouse, the stock levels for the third month for the multi-agent system are assumed to be the stock levels after the second month of operation of the multi-agent system.

The demand is met in both cases as a result of both the multi-agent system and human activity. A comparison of the multi-agent system and human performance over three months is shown in Table 5.5.

Table 5.5

Comparison of Multi-agent System and Human Performance

Time period	The result of multi-agent system	Human result
Initial data	172403	
1st month	148413	155531
2nd month	135550	176903
3rd month	136084	190097

It can be seen that the multi-agent system has reduced stocks and the associated storage costs. The demand has been fulfilled, so it can be concluded that the system is working effectively. If the Inventory management agent is removed from the system, the production is based on intuitive human actions.

Additional experiment to test the performance of a multi-agent system

The aim of the experiment is to test the multi-agent system on the company's data, but for a shorter period of time – 9-month analysis and 8-month performance analysis. During the experiment, the activities of the agents were examined, paying more attention to the activities and results of the Production and Inventory management agents.

Before starting each new case of the multi-agent system, the five steps of adapting the multi-agent system must be performed, as described in the end of Chapter 4.

The processing of various customer requests as well as the choice between different suppliers will not be described in this experiment, as the activities of the agents and their results were described above and the results of the activities of the agents did not change.

The first launch of the Inventory management agent with new data showed that the results of the ABC analysis (Table 5.6) are similar to previous ones (Table 5.1) and differ in one position, which was previously assessed as Class B, and other products differ with a ranking number.

Table 5.6

The Result of ABC Analysis

Product	Rank	ABC analysis result
MChip1	10	A
MChip2	3	A
MChip6	5	A
MChip12	2	A
MChip14	11	A
MChip17	1	A
MChip22	4	A
MChip36	8	A
MChip47	7	A
MChip53	6	A
MChip54	9	A

The Inventory management agent determined the forecasted demand, safety stocks and reorder points. The demand forecast was calculated according to the existing forecasting algorithms and their selection procedure: for each product the multi-agent system forecasting algorithm was applied for the previous 8 months, and these results were compared to the 9th month data. An algorithm that worked with a smaller forecasting error was proposed as a suitable forecasting algorithm for the next month for this product. Similarly, a forecasting algorithm for other products was chosen.
The efficiency of the multi-agent system was tested by comparing the results of the company's employees on 8-month data (See Table 5.7).

Table 5.7

Comparison of Multi-agent System and Human Performance

Time period	The result of multi-agent system	Human result
Initial data	166940	
1st month	146017	170031
2nd month	118116	156209
3rd month	120516	170344
4th month	111495	153455
5th month	105740	157306
6th month	99405	155531
7th month	97662	176903
8th month	96931	190097

It can be concluded from the obtained results that the developed multi-agent system adapts to the specific application case and offers stock reduction and the related costs.

Measuring the efficiency of the developed system application

The developed multi-agent system performance was analysed in accordance with the pre-defined performance measurement indicators (Table 1.1): total production time, inventory storage costs, customer request processing time, and service level.

Total production time

When planning and re-planning production lines, especially if there are capacity constraints on production facilities and long (average monthly) production times, but the demand has to be met within a month or month and a half, then reducing the total production time is an important task.

During the development of the Thesis, the results of planning and re-planning of different production sequences of goods differed for up to two weeks in one month. A person can intuitively or based on his / her experience choose the fastest production sequence, but the duration of production sequence variants can vary from three days to two weeks in a month.

Inventory storage costs

During the research, different stock levels were reached due to the operation of the human and multi-agent system. In both cases, customer demand was satisfied, but the level of stocks in the finished goods warehouse differed (Table 5.4).

Additional experiment had shown the following results: the stock level is gradually reduced as a result of the operation of the multi-agent system. After two months of multi-agent system application, the demand received was low (twice less than the 11-month average), that led to a slower decline in inventories in the following months.

As a result of the multi-agent system application, stock levels were reduced, and storage costs and frozen funds were also reduced; thus, according to the relevant criterion, the objective was achieved.

Customer request processing time

Inter-node collaboration can be assessed by comparing the time spent by a person and an agent on collaboration. Factors influencing the processing time of a request for a person are the following: workload, work interruption and health status, comparison of ordered production and stock levels, and the human factor. As a result, the request processing time may fluctuate as follows:

- for an employee – from 10 minutes to 1 working day,
- for the agent – up to 1 minute.

Service level

All requests were fulfilled, the desired level of service has been reached.

Conclusions of Chapter 5

1. The choice of forecasting algorithms offers to adjust the forecast of each product according to its past values.
2. A comparison of actual demand with a forecast demand for each new demand shall ensure timely adjustments to new production orders.

The results of the practical approbation of the multi-agent system show the efficiency of its application.

RESULTS AND CONCLUSIONS

The aim of the doctoral Thesis was achieved – an approach was developed for creating a multi-agent system that ensures the improvement of supply chain management efficiency. All the set tasks were successfully completed. The following results were obtained during the development of the Thesis:

1. *Analysis and selection of supply chain management efficiency indicators.* The analysis revealed that the most commonly used performance indicators are order fulfillment time, product quality, capacity utilization, customer service level, on-time delivery, customer request processing time and inventory costs. During the development of the Thesis, it was proposed to use the following efficiency indicators to test the efficiency

of the system: total production time, stock storage costs, processing time of customer requests, and service level. These indicators cover the main tasks of the supply chain, and efficiency indicators can be added, if the need arises, to the developed multi-agent system.

2. *Multi-agent systems, their application to supply chain management and their re-application possibilities have been studied.* Multi-agent systems are used for various tasks and research. Although their use has demonstrated improvements in supply chain management, a new multi-agent system needs to be developed for every case. Existing multi-agent systems are not reusable and do not fully cover the requirements for improving supply chain management: ability to work with real-world data, ability to anticipate demand, production planning and rescheduling, ability to communicate with suppliers and customers, inventory management methodology, information sharing between agents and re-use of the multi-agent system. The study concluded that a multi-agent system covering these requirements needs to be developed.
3. *A Multi-agent system architecture has been developed.* Within the Thesis, a heterogeneous system of agents and an architecture of agents based on a model and goal were chosen. For agent interaction, it was suggested to use an ontology as a means of communication between supply chain nodes and to introduce information sharing between agents of one supply chain node. An approach was developed for developing a multi-agent system that improves the efficiency of supply chain management and allows it to be applied by different participants. For re-use of the system, it was proposed to develop a user interface, with the help of which the production process of each individual case can be described for the multi-agent system. The chosen development platform makes it easy to reconfigure the multi-agent system and add or remove additional agents if the need arises.
4. *A reusable multi-agent system has been developed and tested on a real company data.* After the approach had been developed, a multi-agent system was set up and tested on the example of a manufacturing company involved in the production and sale of chips. The Thesis examined the activities of each individual agent, as well as the inter-node communication between the manufacturer and the supplier, and between the manufacturer and the customer. During the investigation, it was verified that the Assembling agent offered a production plan during the operation of the multi-agent system in order to reduce the total production time. Within the Thesis, the processing of different customer requests, the choice between different suppliers and the application of a multi-agent system from one to three months were experimentally tested, analysing the obtained results and comparing them with those obtained for human activities.
5. *The efficiency of application of the developed system has been experimentally proved.* The efficiency of the application of the developed multi-agent system was evaluated using the following efficiency indicators: total production time, stock storage costs, customer request processing time, and service level. As a result of production planning and re-planning of the Assembling agent, the total production time was reduced. The

inventory management agent algorithm with forecast demand and its adjustment when receiving real demand showed better results than without forecast adjustment or compared to human performance, as well as determined order points and safety stocks, thus reducing inventory storage costs. In turn, in the inter-node interaction, the multi-agent system showed faster results as compared to human activity.

Taking into account the results obtained in the Thesis and the experiments performed, the following conclusions were drawn:

1. Multi-agent systems are widely used, but a new multi-agent system must be created in each case. The developed multi-agent system can be adapted to different participants in the supply chain, as it is proposed to represent each node of the supply chain with the same set of agents, which covers the functions of the supply chain, ensuring the improvement of supply chain performance. In turn, the amount of agents can be selected for each application separately.
2. The proposed performance indicators are able to determine the efficiency of application of the developed multi-agent system. These include inventory storage costs, total production time, customer request processing time, and service level, but other efficiencies can be added as needed.
3. The proposed use of ontology and information sharing in a multi-agent system provides a new, hybrid possibility of communication between agents when they avoid the need for communication and use the information necessary for the operation of another agent, thus speeding up the multi-agent system; thus, the first hypothesis was confirmed.
4. The application of the ontology, using the profile ontology for each individual application, ensured the re-use of the multi-agent system, creating a multi-agent system template to improve the efficiency of supply chain management and each new application as an instance of the ontology; thus, the second hypothesis was confirmed.

The results of the practical application of the developed multi-agent system allow to conclude that it is efficient.

Based on the results and conclusions of the Thesis, the directions of further research to improve the developed multi-agent system can be marked. The productivity of the system can be improved by applying RFID technology to the Transportation agent and development of an auction mechanism for the Seller agent. In further research, it is possible to add new forecasting algorithms to the Inventory management agent and test the efficiency of the agent. Another development may involve the use of agents with learning opportunities, adapting to an unknown environment and improving behaviour. This direction of the research arouses more interest in the author's view, and the author believes that learning agents for supply chain management could offer new achievements in improving efficiency.

The developed multi-agent system is the first version of a multi-agent system; it proved the efficiency of operation, but in the course of time it will be supplemented with new functions and algorithms.

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