Application of Operations Research Techniques to the Redesign of the Distribution Systems

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Abstract. The paper presents the application of varies OR techniques to the redesign of the distribution systems. Two real-world case studies are considered. In the first case study the optimization (mathematical programming) approach is discussed. In the second case study heuristic design of different variants of the distribution system supported by object oriented simulation combined with their multiple criteria evaluation is carried out. The following OR techniques and tools are applied: single and bi-criterion mathematical programming, object oriented simulation, multiple criteria ranking methods. The results of computational experiments are presented.

Keywords: multiple criteria decision making/aiding, distribution systems, redesign.

1 Introduction

Operations Research (OR), also called Management Science (MS) is a quantitatively oriented field focused on: analyzing, mathematical modelling and solving various categories of decision problems that arise in organizations, processes and systems [1]. As its name implies OR involves "research on operations". Thus, it is applied in many situations in which the decision maker (DM) faces a complex decision problem that involves planning, control and/ or coordination of various operations (activities) within a certain organization, process and/ or system. OR can be classified as an interdisciplinary field of knowledge located at the boundaries of such areas as: mathematics, probability theory and statistics, computer science, economics and management, engineering and physical sciences, behavioural sciences. The major features of OR are as follows [1]:

- It uses scientific methods and rigid, systematic way of thinking to investigate the problem of concern;
- It looks at the problem at stake from a broad perspective; it applies system approach to problem analysis and solution; thus, OR searches for solutions that attempt to resolve conflicts between different components of the organization / system and satisfy its overall objectives;
- It attempts to find the best/optimal solution for the problem under consideration; instead of improving the status quo OR is focused on identifying the best possible course of action;
- It requires a variety of skills and competences and thus a team approach to carry out a complete study of a certain decision problem.

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The beginnings of OR are associated with the analysis of military operations during World War II. The first British and US OR teams applied different scientific, analytical tools and methods to optimally allocate scarce resources to various military operations (activities). Thanks to their efforts many tactical and strategic military problems have been solved and complex military operations have been rationally planned. Some of their successes include: developing effective methods of using radar, improvement of convoy management and optimization of antisubmarine operations.

Operations Research is a field that developed a spectrum of quantitative methods that support optimal decision making. The following techniques belong to traditional OR techniques [1]: linear and non-linear programming, integer programming, transportation and assignment methods, network algorithms (shortest path and critical path methods; maximum flow and minimum spanning tree algorithms), dynamic programming, game theory algorithms, decision analysis methods (decision trees and decision tables), Markov chains and Markov decision processes, queuing theory methods, inventory control methods and simulation algorithms.

Operations Research also created background for the development of the neighbouring fields, such as: probability theory and statistics, multiple criteria decision making/ aiding, artificial intelligence, data mining, machine learning and many others. In this study the interface between traditional OR techniques and multiple criteria decision making/ aiding (MCDM/A) methods is presented.

MCDM/A is a field which aims at giving the decision maker (DM) some tools in order to enable him/her to solve a complex decision problem where several points of view must be taken into account. MCDM/A concentrates on suggesting "compromise solutions", taking into consideration the trade-offs between criteria and the DM's preferences [2]. The decision processes based on multiple criteria analysis involve the following parties: the decision maker (DM), stakeholders and analyst. MCDM/A methods are computer based tools that assist DMs in solving multiple criteria decision problems. Those problems are the situations in which having defined a set of actions (decisions, alternatives) A and a consistent family of criteria F the DM tends to: define a subset of actions (decisions, alternatives) being the best on F (choice problematic), divide the set of actions (decisions, alternatives) into subsets according to certain norms (sorting problematic), rank the set of actions (decision, alternatives) from the best to the worst (ranking problematic). The classification of MCDM/A methods corresponds to the above classification of multiple criteria decision problems. Thus, one can distinguish MCDM/A choice (optimization) methods, MCDM/A sorting methods and MCDM/A ranking methods. Many MCDM/A specialists suggest also the division of MCDM/A methods based on their approach to aggregating global preferences of the DM [17]. Based on that division criterion one can distinguish two major streams of methods i.e.: the American school based on multiatribute utility theory and the European school based on the outranking relation. Well-known representatives of those streams are: AHP [3] and UTA [4] methods versus ELECTRE [2][5], Oreste [6] and PROMETHEE [7] methods, respectively.

The paper presents the application of OR techniques to the redesign of a certain distribution system. The distribution system is defined [8] as a set of such components as: infrastructure (roads, warehouses), human resources, fleet, business processes and organizational rules which are responsible for planning, implementing and controlling the physical flows of products from points of origin to points of destination. Those components should match together to assure the efficiency and effectiveness of the whole distribution system. That is why its design and redesign is a very complex task [9][10]. The redesign process is connected with significant changes in the structure of the distribution system [11] i.e. changes in the location of warehouses, reassignment of tasks and redistribution of inventory between warehouses, reassignment of roles and responsibilities among supply chain points, changes in a transportation network etc.

Based on the classical division of the decision problems [2][5] one can perceive the redesign of the distribution system as a choice (mathematical programming) problem or as a ranking problem. In the first case the decision maker (DM) is looking for the optimal structure (design) of the system and the decision problem is formulated as an optimization problem. In the second case different development scenarios (alternative solutions) are designed, evaluated and ranked from the best to the worst. In the design phase, different solutions concerning transportation, organizational rules, material and information flow, human resources, infrastructure etc. are proposed by the experts. In the evaluation phase the selection of the best candidate (distribution system) is carried out. Both of the above approaches are presented in this study.

2 Methodological Background

In general, practically oriented OR studies usually involve the following phases [1]:

- Definition and thorough recognition of the problem of interest combined with its precise, verbal description;
- Formulation of the mathematical model representing the problem and collection of the relevant data required to run the model;
- Selection / customization and/or development of computer-based procedures capable to generate solutions to the problem considered;
- Testing and adjusting the model, often called model validation; running a series of computational experiments to generate different samples of solutions;
- Implementation of the selected, most desired (optimal) solution.

This scheme has been applied in the below characterized case studies. Due to specific character of the decision problems considered in particular case studies the above mentioned generic phases of OR – oriented projects have been customized. In both cases the decision problems have been recognized and verbally described. Different decision models have been formulated to represent decision situations in case studies 1 and 2, respectively. In case study 1 the decision problem has been formulated as a single and bi – criterion mathematical programming problem. It involved the definition of the decision variables and parameters, objective function(s) and constraints. In case study 2 a combination of two OR approaches has been utilized. The first model of the object oriented simulation has been applied to generate different variants of the distribution system, while the second one – of the multiple criteria ranking problem has been used to evaluate and rank the considered distribution systems. In both case studies appropriate computer – based procedures have been utilized to solve the respective decision problems. In case study 1, computer implementations of simplex [1] and gradient methods [1] have been utilized to solve single criterion, linear and nonlinear formulations of the decision problem, respectively. To this end a commercial solver MS Excel Solver – Premium Solver Plus by Frontline Systems has been applied. In case study 2, stochastic simulation procedures implemented in the computer package ExtendSim have been applied to observe the operations of different variants of the distribution system. Those variants have been evaluated and ranked with the application of the multiple criteria ranking method – ELECTRE III and AHP (Analytical Hierarchy Process).

3 Case Studies

Case study 1 – Single and bi – criterion optimization of the distribution system. Application of mathematical programming [12]. The first case study focuses on the redesign of the distribution system for an international company based in Warsaw, Poland. The primary concern of the project is to define the number and the location of the warehouses as well as the service area of each warehouse. The considered distribution system is managed by the manufacturer of cosmetics, detergents and washing articles. The annual turnover of the company is roughly 100 million Euro (400 million Polish zloty – PLN). 85% of the turnover is generated at the Polish local market and the remaining 15% is an export to Eastern European countries. At the Polish market the company's products are mainly sold to wholesalers (60% of sales) and the chains of large retailers (hipermarkets, supermarkets) – 20% of sales. The company is concerned about its costs, including distribution costs, which amount to 6.5% of sales. Its major focus, however, is the enhancement of the customer service level. The company would like to increase the market share and make the company's products available at each retail shop. In the opinion of the company's top management this goal can be obtained through the redesign of the distribution system, which should be more reliable and more flexible. The target for the distribution system is to fulfill each customer's order and deliver the required products within 24 hours. Delivery time should be further decreased in the next years. This should satisfy customers' expectations and requirements and make the company's slogan: "Our products in each Polish home", rational.

The existing distribution system is based on two production plants and two warehouses located in cities A and B, next to the production facilities. Due to the fact that the production profile and the product portfolio are different in the production plants in A and B trunking between warehouses is required. It amounts to 45% of the total number of tkm covered by the distribution system. Each warehouse has a certain area to cover, which corresponds to a concrete number of customers served. The total number of customers is about 400. The products are delivered by 24 tractor – semi trailer units with a capacity of 33 Europallets each.

As far as delivery time is concerned, the existing distribution system guarantees a 48 hour deliveries in the majority of cases and 72 hour deliveries to the most distant customers. The customer service level (defined as a product availability percentage) is 95%. Customers are not satisfied with timeliness and frequency of deliveries. Thus, the first objective of the project is to minimize the total distribution costs, including the warehousing, transportation and capital in stock costs. The second objective is to minimize the delivery time, which may be reduced by many actions influencing different stages of the order fulfillment process. The actions considered in this study may influence riding time. Thus, the minimization of the riding time is the second objective of the study.

The decision problem is formulated in terms of multiple objective mathematical programming with binary and continuous variables.

Data. The following data is used in the model:

I - the number of potential locations of warehouses,
J - the number of regions that have to be assigned to the warehouses,
DA_j - annual demand of region j for products of production plant A in [pallets], $j = 1,...,J$,
DB_j - annual demand of region j for products of production plant B in [pallets], $j = 1,...,J$,
TC_{ij} - average transportation cost from warehouse at location i to region j in [PLN/pallet], $i = 1,...,I$, $j = 1,...,J$,
TCA_j - average transportation cost from production plant A to warehouse at location i in [PLN/pallet], $i = 1,...,I$,
TCB_j - average transportation cost from production plant B to warehouse at location i in [PLN/pallet], $i = 1,...,I$,
TT_{ij} - average travel time from warehouse at location i to the first customer in region j in [min], $i = 1,...,I$, $j = 1,...,J$,
PHC_i – cost of pallet handling in warehouse at location i, $i = 1,...,I$,
CRT - current average pallet rotation time in [days], i.e. the average number of days that a pallet spends in the current distribution system,
CCA - average daily cost of capital in stock per pallet produced in production plant A in [PLN/day],
CCB - average daily cost of capital in stock per pallet produced in production plant B in [PLN/day],
MCC_i - minimum annual cost of capital in stock in warehouse at location i related to the safety stock of pallets,
ML - maximum load of vehicles used for transportation from production plants to warehouse,
DY - average number of working days in a year.

Decision variables. Two groups of decision variables are considered:

$y_i \in \{0, 1\}$, $i = 1,...,I$, equals to one if warehouse at location i is included in the plan, and 0 otherwise.
$x_{ij} \in \{0, 1\}$, $i = 1,...,I$, $j = 1,...,J$, equals to one if region j is assigned to warehouse at location i, and 0 otherwise.

Constraints. The first group of constraints assures that regions are assigned only to warehouses included in the plan:

$$x_{ij} \le y_i, \qquad i = 1,...,I, j = 1,...,J. \tag{1}$$

The second group of constraints assures that each region is assigned to exactly one warehouse:

$$\sum_{i=1}^{I} x_{ij} = 1, \qquad j = 1,\ldots,J. \tag{2}$$

Some additional constraints added to the model in order to obtain a linear model are described below.

Objective functions. Two objectives are considered in the model:

- *TDC* - total annual cost of distribution,
- *MRT* - maximum riding time to the first customer on a route.

Both objectives are minimized.

The first objective is defined in the following way:

$$TDC = TTC + TPHC + TCC,. \tag{3}$$

where: *TTC* denotes total annual transportation cost, *TPHC* denotes total annual cost of pallets handling in the warehouses, and *TCC* denotes total annual cost of capital in stock.

Total annual transportation cost takes into account transportation from production plants to warehouses and transportation from warehouses to the customers in the regions. It is defined in the following way:

$$TTC = \sum_{i=1}^{I} y_i \left(TCA_i \sum_{j=1}^{J} x_{ij} DA_j + TCB_i \sum_{j=1}^{J} x_{ij} DB_j \right) + \sum_{i=1}^{I} \sum_{j=1}^{J} x_{ij} TC_{ij} (DA_j + DB_j) \tag{4}$$

Total annual cost of pallets handling in the warehouses is defined in the following way:

$$TPHC = \sum_{i=1}^{I} y_i PHC_i \left(\sum_{j=1}^{J} x_{ij} DA_j + \sum_{j=1}^{J} x_{ij} DA_j \right), \tag{5}$$

Total annual cost of capital in stock is defined in the following way:

$$TCC = \sum_{i=1}^{I} y_i \max \left\{ MCC_i, \sum_{j=1}^{J} x_{ij} DA_j CCA(CRT + DHA_i) + \sum_{j=1}^{J} x_{ij} DB_j CCB(CRT + DHB_i) \right\} \tag{6}$$

where: DHA_i and DHB_i is an average headway of deliveries for production plants *A* and *B*, respectively, defined in the following way:

$$DHA_i = ML / \left(\sum_{j=1}^{J} x_{ij} DA_j / DY \right), \tag{7}$$

$$DHB_i = ML / \left(\sum_{j=1}^{J} x_{ij} DB_j / DY \right). \tag{8}$$

Total annual cost of capital in stock is not linear as it uses operator max. In order to obtain linear model we add I continuos variables cc_i interpreted as cost of capital in stock in warehouse at location i. Furthermore, we add two groups of constraints:

$$cc_i \geq MCC_i, \quad i = 1,...,I, \qquad . \tag{9}$$

$$cc_i \geq \sum_{j=1}^{J} x_{ij} DA_j CCA(CRT + DHA_i) + \sum_{j=1}^{J} x_{ij} DB_j CCB(CRT + DHB_i) \\ , i = 1,...,I. \tag{10}$$

Total annual cost of capital in stock is defined as:

$$TCC = \sum_{i=1}^{I} y_i cc_i \ . \tag{11}$$

Maximum riding time to the first customer on a route is defined in the following way:

$$MRT = \max\{x_{ij} TT_{ij}\}. \tag{12}$$

Again, this objective is not linear. In order to obtain linear model we add a continuos variable *mrt* and the following group of constraints:

$$mrt \geq x_{ij} TT_{ij}, \quad i = 1,...,I, j = 1,...,J. \tag{13}$$

Maximum riding time to the first customer on a route is then equal to a new variable:

$$MRT = mrt. \tag{14}$$

Finally, we obtain a mixed binary bi-objective mathematical programming problem with $I \times J + J$ binary variables and $I + 1$ continuous variables defined in the following way:

minimize: $TCC = \sum_{i=1}^{I} y_i cc_i$

minimize: $MRT = mrt$

subject to:

$$x_{ij} \le y_i, \quad i = 1,...,I, j = 1,...,J$$
$$\sum_{i=1}^{I} x_{ij} = 1, \quad j = 1,...,J$$
$$cc_i \ge MCC_i, \quad i = 1,...,I \tag{15}$$
$$cc_i \ge \sum_{j=1}^{J} x_{ij} DA_j CCA(CRT + DHA_i) + \sum_{j=1}^{J} x_{ij} DB_j CCB(CRT + DHB_i)$$
$$, i = 1,...,I$$
$$mrt \ge x_{ij} TT_{ij}, \quad i = 1,...,I, j = 1,...,J$$
$$y_i \in \{0, 1\}, i = 1,...,I$$
$$x_{ij} \in \{0, 1\}, i = 1,...,I, j = 1,...,J$$

In the analyzed case $J = 39$, $I = 49$, thus the problem has 1900 binary variables and 50 continuous variables.

Case study II – heuristic redesign of the distribution system supported by object oriented simulation and multiple criteria evaluation of the variants of the distribution system [14][15]. The problem considered in case study II focuses on the design and evaluation of alternative logistic solutions for the distribution system, which consists of 24 warehouses/ distribution centers (DCs) uniformly spread all over Poland. The system is owned and operated by a medium sized trade-distribution company generating an annual turnover of 55 mln Euro (210 mln PLN). The company, with a market share of 11% and the overall labor size of 160 employees belongs to major players at the Polish electrotechnical market. The analyzed distribution system can be divided into 5 echelons (Figure 1): a suppliers' level (SL) – 75 manufacturers and distributers, a central level (CL) – 1 central warehouse (CW), a regional level (RL) – 12 DCs, a local level (LL) – 11 DCs and a customers' level (CuL) – 400 customers. It distributes and delivers for sales a full range of electrotechnical products from fuses and bulbs to pylons, and from sockets and switches to electrical wires, with a total number of 38,5 thousand units, divided into 56 groups. The DCs are differentiated by their locations and areas to serve, building structures and equipment, warehousing capacity, inventory portfolio, crew size, etc. All the goods (products, materials) are moved in the distribution system by road transportation, which is partially outsourced and partially carried out as in-company activity by a fleet of 55 vehicles including 38 vans and trucks.

From the OR perspective the analysis of case study II can be split into two major phases. In phase I the variants – development scenarios of the distribution system are designed / constructed and in phase II they are evaluated and ranked from the best to the worst.

In phase I, based on the comprehensive diagnosis (SWOT analysis) of the above described existing distribution system (variant 1-AI) its strengths and weaknesses have been recognized. To reduce disadvantages of the distribution system its redesign has been proposed. The system is restructured heuristically, with the application of common sense and expert knowledge. In the redesign process major objectives of the management team of the trade-distribution company, including: improvement of the customer service (minimizing delivery time) and enhancement of efficiency (maximizing rotation level of inventories and fleet, infrastructure utilization) are taken into account. The restructuring of the distribution system consists in the introduction of its certain improvements and changes, including: redefinition of the location and number of the DCs, reassignment of their customers and service areas, enhancement of the logistic infrastructure and equipment used in the DCs, redesign of the warehousing space and changes in warehousing capacities, changes in the organization of the transportation system, redefinition of the fleet composition, reshaping of the inventory portfolio and balancing the inventory levels, reconstruction and improvement of the information and material flows, reassignment of tasks and responsibilities in the distribution system, redefinition of duties for the employees, rationalization of the crew size. As a result of the proposed changes 6 alternative variants - development scenarios of the distribution system (variant 2 - AII, variant 3 - AIII, variant 4 - AIV, variant 5 - AV, variant 6 - AVI, variant 7 - AVII) have been constructed. The heuristic construction of variants is supported by object-oriented simulation carried in the computer-based tool ExtendSim. The operations of the designed variants are simulated and certain parameters characterizing them are generated. The structure of the simulation model is presented in Figure 1. The model reflects the 5 echelon structure of the distribution system, with five levels: SL, CL, RL, LL and CuL, four of which include the hierarchical objects denominated by $G_i^{SL}, G_i^{CL}, G_i^{RL}, G_i^{LL}$. These objects are responsible for the generation of information characterizing the structure and the course of actions of the ordering process at particular levels. They are linked with another set of hierarchical objects $N_N^{SL}, N_N^{CL}, N_N^{RL}, N_N^{LL}, N_N^{CuL}$, representing suppliers (SL), distribution centres (CL, RL and LL) and final customers N_N^{CuL}, respectively. They are supplied with the information regarding the content and characteristics of the orders, e.g.: number of pallets ordered, type of the products ordered, name of the customer, distance between supplier / distribution centre and the customer. The physical flow of products is represented by the hierarchical objects denominated by $G_k^{SL}, G_k^{CL}, G_k^{RL}, G_k^{LL}$. The arrows present the connections between suppliers, distribution centers and customers. This generic structure of the simulation model is customized to specific features of variants A_{II}, A_{III}, A_{IV}, A_V, A_{VI} and A_{VII}. The designed and simulated variants represent different level of changes from superficial and evolutionary to very comprehensive and radical. They differ for example by the following features:

- number of echelons (SL, CL, RL, LL and CuL) ranging from 3 to 5,
- total number of warehouses in the distribution system ranging from 1 (supported by 49 retail shops) to 32; different locations of the warehouses;
- number of warehouses at the central level ranging from 1 to 4;
- share of the company owned and managed warehouses ranging from 0% (complete outsourcing) to 100% (full ownership);
- share of transportation activities carried out at different echelons of the distribution system by the company, ranging from 0% to 100%;
- number of employees ranging from 120 to 250.

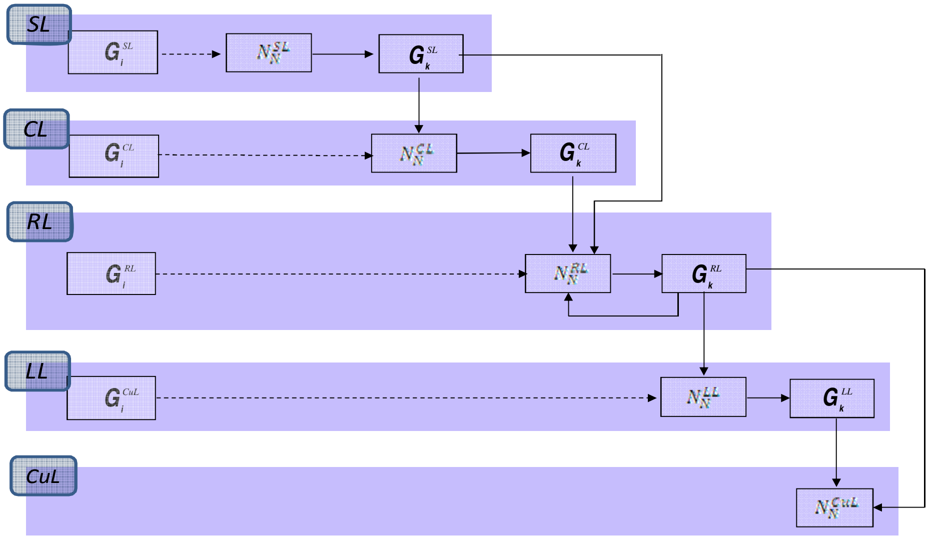

Fig. 1. The generic structure of the simulation model for the distribution system

As a result the variants of the distribution system are characterized by different measures of performance/ evaluation criteria that represent the interests of different stakeholders, including: owners/managers of the distribution system, final customers, haulers, employees involved in the distribution process.

In phase II, the evaluation process of the proposed variants is carried out. It is based on the application of MCDM/A methodology. Two MCDM/A methods: ELECTRE III [2][13] and Analytic Hierarchy Process - AHP [3] are used to rank the variants. Phase II involves the definition of criteria, construction of the evaluation matrix, definition of the DM's preferences and computational experiments resulting in the generation of final rankings.

In the analyzed case the following evaluation criteria, constituting a so called consistent family of criteria [2][13], are taken into account:

- C_1 – average delivery time [days], minimized criterion;
- C_2 – dispersion of warehouses [%], maximized criterion;
- C_3 – share of distribution costs in the total sales [%], minimized criterion;
- C_4 – average rotation level of inventories in a distribution system [days], minimized criterion;
- C_5 – difference between the levels of investments and divestments [PLNx1000], minimized criterion;
- C_6 – the company's ability to accept changes [%], maximized criterion;
- C_7 – turnover per employee [PLNx1000], maximized criterion;
- C_8 – MIRR (Modified Internal Rate of Return) [%], maximized criterion;
- C_9 – NPV (Net Present Value) [PLNx1000], maximized criterion;
- C_{10} – market share [%], maximized criterion.

The evaluations of alternatives on all criteria are presented in the matrix of performances (see Table 1).

Table 1. Matrix of performances for alternative distribution systems

Alternative distribution systems	Criteria									
	C_1 [ds]	C_2 [%]	C_3 [%]	C_4 [ds]	C_5 [PLN x 10^3]	C_6 [%]	C_7 [PLN x 10^3]	C_8 [%]	C_9 [PLN x 10^3]	C_{10} [%]
A_I	4	33	4.7	32	0	52.7	1313	31	6750	11
A_{II}	2	33	5.5	43	4855	60.1	1528	15	1188	14
A_{III}	3	27	4.3	31	-50	61.6	2148	172	4321	11
A_{IV}	2	33	5.2	45	2610	55.3	1838	9	8940	16
A_V	4	33	4.9	46	10475	58.8	1989	36	430	14
A_{VI}	3	50	4.4	28	10320	59.5	3049	11	28684	21
A_{VII}	1	60	4.6	33	-385	83.0	2064	41 65	21200	24

The phase of defining the DM's preferences allows for taking into account specific and subjective aspirations and expectations of the DM. In general, the majority of the DM's models of preferences include: the importance of criteria and the DM's sensitivity with respect to the changes of the values of criteria. The models of the DM's preferences differ in both methods. In the ELECTRE III method it is determined by weights w_j for each criterion and the indifference q_j, preference p_j, and veto v_j thresholds. In the AHP method pairwise comparison judgements between criteria and variants are carried out. These pairwise comparisons are quantified by the standard "one – to – nine" measurement scale: 1 – equally preferred; 3 –moderately preferred; 5 – strongly preferred; 7 – very strongly preferred; 9 – extremely strongly preferred. The intermediate judgements like: 2, 4, 6, 8 can be used if necessary The model of the DM's preferences for both methods is presented in Table 2.

Table 2. Model of the DM's preferences in ELECTRE III and AHP methods

	ELECTRE III				AHP									
Criteria	w_j	q_j	p_j	v_j	Criteria									
					C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
C_1	9.8	0.6	1.1	2.2	1	2	2	1	5	7	5	5	5	4
C_2	8.1	8.9	16.1	30.4	1/2	1	1	1/3	4	5	4	3	3	2
C_3	8.2	0.2	0.5	1.1	1/2	1	1	1/3	4	5	4	3	3	2
C_4	10.0	2.0	4.7	8.3	1	3	3	1	7	7	7	5	5	3
C_5	6.1	1964.3	4071.5	9785.7	1/5	1/4	1/4	1/7	1	1	1	1/2	1/2	1/4
C_6	6.0	4.7	11.7	23.1	1/7	1/5	1/5	1/7	1	1	1/2	1/2	1/2	1/4
C_7	6.3	142.9	303.6	503.6	1/5	1/4	1/4	1/7	1	2	1	1/2	1/2	1/3
C_8	6.7	25.4	50.7	98.6	1/5	1/3	1/3	1/5	2	2	2	1	1	1/3
C_9	6.6	2458.4	5000	9833.4	1/5	1/3	1/3	1/5	2	2	2	1	1	1/3
C_{10}	7.6	2.1	5.2	10.2	1/4	1/2	1/2	1/3	4	4	3	3	3	1

4 Computational Experiments

Case study I. In case study I the optimization of the distribution system has been performed with the application of the extended version of MS Excel Solver – Premium Solver Plus by Frontline Systems. It solves linear problems composed of up to 2000 variables and 400 constraints. The experiments have been divided into two steps: the first one, based on single objective optimization and the second one focused on bi-objective optimization.

In the first step, only one objective - total distribution costs was used, to demonstrate the comparison between the existing and the optimal distribution systems (see Table 3.). The optimal system is composed of 7 warehouses.

Table 3. The comparison between the existing and the optimal distribution system (single objective optimization)

Distribution system	Number of warehouses	Total annual distribution costs [PLN]	Ridind time [h:mm]
Existing	2	9 924 300	9:22
Optimal	7	9 357 784	6:09

The interesting observation is that single objective optimization resulted in reducing both total distribution costs (by 566 516 PLN) and the riding time (by 3 hours and 13 minutes). Thus from the multiple objective point of view the optimal distribution system dominates the current one. As a result of the optimization process new definition of service areas (new assignment of 49 regions to 7 warehouses) for each warehouse was obtained.

In the bi-objective optimization ε-constraints method [16][17] has been used to generate a representative sample of Pareto-optimal solutions. In the computational procedure riding time was being constrained from 6 to 2 hours. The result of the bi-objective optimization is a set of Pareto-optimal distribution systems presented in Figure 2. The generated distribution systems are composed of 7 – 23 warehouses. The results show the existing cost-time trade-offs. For instance, riding time reduction from 6:09 to 5:23 (by 46 min) results in 2 more warehouses in the distribution system and additional costs of 186 000 PLN, while riding time reduction from 2:44 to 2:41 (by 3 min) also results in 2 additional warehouses in the distribution system and corresponding increase in total distribution costs of 548 000 PLN.

Another interesting observation comes from the comparison of the existing distribution system (see Table 3) with a set of Pareto-optimal distribution systems (see Figure 2). Maintaining the same level of the total distribution costs (around 9 900 000 PLN) one can replace the existing distribution system (with 2 warehouses) by the Pareto – optimal one (with 10 warehouses) and shorten the riding time from 9:22 to less then 4:20 (55% reduction). The distribution system with 10 warehouses has been finally selected as the most desired option and practically implemented.

Riding time [h:mm]	Total distribution costs [PLN]	No. of warehouses
2:41	12 972 507	23
2:44	12 424 210	21
2:59	11 653 423	18
3:28	10 813 246	15
4:00	10 090 964	12
4:20	9 802 832	10
4:35	9 746 413	10
5:23	9 543 711	9
6:09	9 357 784	7

Fig. 2. Pareto-optimal set of the distribution systems in the numerical and graphical form

Case study II. In case study II computational experiments refer to two phases, i.e. designing and evaluating the variants of the distribution system. In the design phase an object-oriented simulation tool ExtendSim is applied. This is a user friendly package which can be used to construct operational model of complex systems in a graphical form without advanced programming skills [18]. It is typically used in transportation, logistics, business processes redesign, manufacturing, as well as in healthcare, service and communications industries. This tool is based on the application of continuous and discrete-event simulation. It provides hierarchy structure of a model and a comprehensive library of objects that can be adjusted to specific environments and concrete decision problems.

The example of simulation modeling of the distribution system is presented in Figure 3. One can distinguish two areas A and B, which correspond to the software functionalities of information generation and information memorization, respectively. In the area B parameters of incoming orders, such as: starting distribution center n_{NS} as a place of incoming order; ending distribution center/ final customer n_{NE}, which placed an order for products; number of ordered products $\tilde{q}_{kn}$ within the assortment k; distance $s^{n_{NS}n_{NE}}$ between n_{NS} and n_{NE}, speed value $\tilde{v}^{n_{NS}n_{NE}}$ between n_{NS} and n_{NE}, are modeled. This information is generated by objects presented in the area A and sent to the

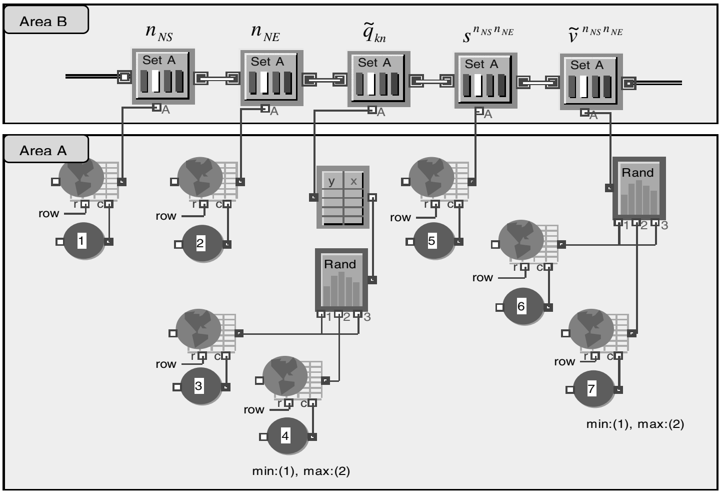

Fig. 3. Sequence of objects representing information flow in the simulation model of the distribution system

objects in area B. Objects in the area A are connected with spreadsheets of MsExcel including data collected during the analysis of the distribution system. Parameters of a random character, such as: $\tilde{q}_{kn}$ and $\tilde{v}^{n_{NS}n_{NE}}$ are modelled by objects Rand, which are responsible for applying different patterns of random variables distributions.

During the simulation process different parameters of the designed variants of the distribution system are generated (estimated), including: daily number of departures of vehicles and EURO pallets dispatched at different levels of the distribution system, unit transportation and warehousing costs, total distance covered by transportation fleet per day, utilization of warehouses, forklifts and operators, average queue length of vehicles waiting for unloading, inventories rotation indexes, etc. Those parameters allow to compute the values of criteria C_1 to C_{10}, presented above.

In the evaluation phase two MCDM/A methods, including ELECTRE III and AHP are applied. The algorithm of the ELECTRE III method computes the following parameters[13]: concordance index, discordance index and the outranking relation. Based on that, two complete preorders (descending and ascending) are generated[13]. Their intersaction constitutes the final ranking. In the AHP method[3] the matrixes of normalized absolute weights are constructed at each level of the hierarchy and an eigenvalue problem[3] is solved for each matrix. In the next step global consistency indexes[3] are computed and checked for feasibility. In the last step utilities[3] for each variant are calculated and based on that their ranking is constructed. Figure 4 presents the final rankings of the distribution system development scenarios generated by ELECTRE (a) and AHP (b) methods.

The comparative analysis of both rankings reveals a high degree of similarity between them ELECTRE III method indicates that the best solution is the alternative A_{III}. This alternative involves the minimum number of changes in the distribution

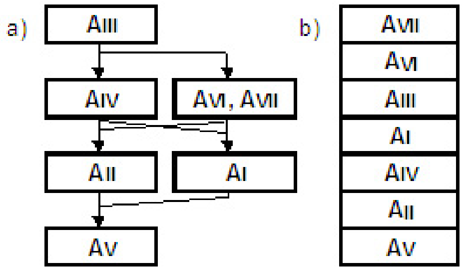

Fig. 4. Final rankings of the development scenarios of the distribution system generated by: a) ELECTRE III method, b) AHP method

system. Its advantage is a high MIRR index and the lowest (in comparison with other alternatives) distribution costs. The main disadvantage of A_{III} is a low market share (almost 11%) and long average delivery time (3 days). The AHP method suggests that alternative A_{VII} is the best solution. A_{VII} is characterized by the most radical changes in the distribution system. In this case the redesign guarantees a high market share (24%) and low distribution costs. The average delivery time is 1 day. Both final rankings reject alternatives A_V and A_{II}. The evaluation of alternatives A_I and A_{IV} is ambiguous.

Based on the results of the computational experiment, the author of the paper suggests the following stepwise path of changes:

- Introduction of the evolutionary changes represented by AIII in the first phase.
- More radical transformation from AIII to AVII in the second phase.

5 Conclusions

The paper presents practical application of OR techniques to the redesign of the distribution system. The classical OR methodology is presented, including: problem recognition and verbal description, formulation of the mathematical model, selection of computer-based methods capable of solving the considered decision problem, computational experiments resulting in the selection of the most desired solution, implementation of the selected solution.

The problem of redesigning the distribution system has been presented in two alternative ways:

- In case study I as a single and bi-objective choice problem, formulated as a mathematical programming problem;
- In case study II as a multiple criteria ranking problem in which the definition of the variants (distribution systems) has been supported by object – oriented simulation.

The article demonstrates the application of the following techniques: single and bi-objective optimization, object oriented simulation, multiple criteria ranking methods.

The paper shows practical applicability of the proposed approach. In case study I the optimal distribution system is 6% more efficient than the existing one (cost-wise) and the finally selected Pareto – optimal distribution system provides an enhanced by 55% customer service (reduction of the delivery time). In case study II both selected solutions (A_{III} and A_{VII}) assure noticeable financial and market-oriented improvements. An interesting step-wise implementation of the changes is proposed.

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