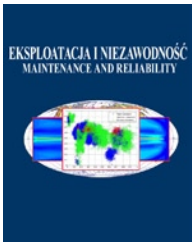

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# Models of vehicle service system supply under information uncertainty

Indexed by:

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## Highlights

- The national vehicle service system structure consists of three different segments.
- Incorrect logistics decisions in each of segments strongly influences financial losses.
- Information uncertainty is a key factor influencing supply failures in each segment.
- The risks associated with spare parts purchase can be minimized using authorial algorithm.
- Logistical support provides competitiveness of workshops at low demand for maintenance.

## Abstract

The paper presents problems of decision-making for planning and implementation of vehicle service system supplies with spare parts under incomplete information. The lack of effective supply planning models using artificial intelligence principles contributes to widening the gap in the problem. The analyses confirm that information uncertainty is one of the main factors in supply failures leading to financial losses for both vehicle service stations and supply companies. Authors structured national vehicle service system by classifying its three different segments. This allowed the identification of risks of making incorrect logistics decisions in each of defined segments. It has been shown that the supply planning process in each of segments is carried out according to different rules. Authorial decision models for each of segments are then presented. The models can be used as a tool to support and improve supplying vehicle service stations in conditions of information uncertainty. In the application part, a proprietary algorithm has been developed to solve proposed models.

## Keywords

vehicle service stations, spare parts, information certainty, supply chain, decision model.

## 1. Introduction

In 2010, the number of cars used all over the world exceeded one billion pieces. Over 50% of all vehicles were used in the USA and EU. Every year, 20 million new cars get used on USA roads, and in the EU it is 14 million, with 531 cars for every 1,000 inhabitants [5]. This is associated with a significant increase in demand for services in logistics segment of production and distribution of new vehicles (FL – Forward Logistics) and the market for supplying spare parts and accessories (RL – Reverse Logistics) [9]. According to the traditional approach, the supply chain for newly manufactured cars begins at the place of their production and includes distributors, wholesalers and retailers and ends at cars recipients. Process improvement results primarily from improving the coordination of activities of individual participants in the supply chain and thus minimizing the risk of not completing a supply task [31].

During the vehicle lifetime, generally, two conditions are noted: usage and service. The state of use means using the vehicle for its intended purpose, i.e. the movement of people and loads in time and space [3, 29]. On the other hand, servicing is a set of organizational and technical activities aimed at restoring and maintaining the serviceability of a vehicle [50].

At present, apart from technological and economic factors, an environmental factor is gaining significance in restoring vehicle parts to fitness (regeneration) [40, 43]. The use of regenerated parts reduces negative impact of production processes on the environment [13].

The quality of actions carried out as part of spare parts supply chains is important for the effectiveness of all segments of automotive industry. The COVID-19 pandemic situation caused a temporary collapse in new cars production, hence the expectation that after 2026 the value of whole automotive segment will reach only about 810 billion $ [1]. This means that the condition of entire automotive industry will largely depend on maintenance services. In addition, as the number of cars sold increases, the number of end-of-life vehicles increases as well and as a consequence, the huge ELVs (End-of-Life Vehicles) segment is created [47].

Analysis of practices shows that the reasons for temporary or complete withdrawal of vehicles from operation are primarily:

- need to ensure required by regulations safety level for vehicles (through modernization of car systems or components, e.g. EGR exhaust gas recirculation system),
- need for the repair vehicles after damaging event (collisions, accidents),
- returns of newly manufactured vehicles (options included in contracts if structural or factory defects are found),
- need to renovate cars for prestigious, social or business reasons,
- accelerated aging of materials used for structural elements (body and chassis).

All these requirements increase demand for car service stations and force constant improvement of service offer. It is more important

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when transport companies, regardless of the business profile and vehicle fleet size, focus on transport tasks requiring high readiness of their fleet. On the other hand, cars, regardless of brand or purpose, need more and more time-consuming diagnostic and repair services over passing time. This results in more often temporary decommissioning of vehicles for random technical reasons. Hence the demand for repairs in so-called DIFM (Do-It-for Me) segment increases.

As part of repairs, various activities are performed, including [6]:

- after accident and emergency repairs;
- modernization of car systems and components to meet new legislative requirements;
- regeneration of worn parts and removal of factory defects located on the basis of measurements and diagnostic tests;
- withdrawal and recycling of used cars.

Such a range of tasks places expectations on the organization of supplying automotive vehicle service stations with spare parts. In addition, the lack of unified service repair technologies results in both a multitude of approaches in designing spare parts supply chains for these stations and a high flexibility in delivery requirements. Customers are looking for vehicle service stations guaranteeing high quality and timely services, and are not willing to accept extended repairs. Moreover, due to random nature of service requests, spare parts supply chains are characterized by high level of orders uncertainty. In addition, the order specification is created in short planning horizon and under uncertain circumstances (see works: [18, 27]).

To avoid unplanned interruptions in car repair process caused by the lack of appropriate spare parts specific methods can be used. This paper presents original decision models reflecting processes of supplying automotive service stations with such parts. The starting point was the analysis of automotive market segments to identify basic problems of the spare parts supply network and analysis of a wide spectrum of literature in this area. The models assume that properly functioning supply network of vehicle service stations, fulfilling orders for spare parts, depends largely on the certainty of information about repairs or specific inspections. Because the process of ordering missing spare parts is a random process resulting from various types of vehicle damage, therefore the uncertainty of information about spare parts order specification is a factor negatively affecting the efficient operation of service stations. A longer waiting for parts slows down the work of a station, but also negatively affects the quality of services, which is an unacceptable situation in the era of high competition on the service market.

Developed models are equipped with innovative optimization algorithm minimizing the risk of ordering unnecessary or mismatched parts, taking into account uncertain information resulting from the information flow between individual participants of the supply process. The proposed algorithm is a modification of classical genetic algorithm widely described in the literature. This algorithm shapes the supply chain in a way to keep orders volume or ordered item lists subjected to acceptable risk that guarantees continuity of vehicle repair processes.

## 2. Characteristics of automotive market segments in the aspect of maintenance services

Data from the European Automobile Manufacturers Association (ACEA) [4] show that the average age of cars, which in 2018 was around 14 years, is a factor influencing development of repair and maintenance services. Half of registered cars in 2018 were those aged 11-20 years, the next 15% were above 20 years old. Passenger cars in the EU have an average working age of 11.1 years, vans 11 years and trucks 12 years [4]. This results in a relatively high failure rate of vehicles due to various faults or damage. In addition, during the operation period over 60% of cars are subject to accidents, some of which are intended for cassation. The average car travels over 320 thousand km during the life cycle and consumes 3 sets of tires. During the car's life cycle, its owner devotes an average of PLN 16,000 (EUR 3,500) to repairs [22].

The analysis of automotive market show changes in the structure of vehicles on roads. For example, in 2018, 532 thousand brand new vehicles were purchased in Poland. In the first three quarters of 2019 410.8 thousand new passenger cars (+ 1.9% y / y) were registered [45]. The number of registrations of vehicles with alternative drives is growing rapidly [44, 49]. 28.6 thousand cars with alternative drive have been registered since the beginning of the year (+ 60.3% y/y). Nevertheless, the share of used cars not older than 4 years bought in 2018 increased by 10.7%, i.e. by nearly 1 percentage point. The share of the oldest, over 10-year-old vehicles, increased by 0.7 percentage points and represents 54% of all cars.

Technological progress makes newly manufactured cars more technically advanced. This results in the shrinking of the Do-It-Yourself (DIY) segment [7, 8]. Importantly, the value of the Polish spare parts market as well as diagnostic and repair work has been growing for many years and at the turn of 2019/2020 exceeded 30 billion PLN. 640,000 spare parts pieces go to garages and shops every day in Poland [22].

In view of the above, it can be said that basic problems associated with spare parts supply are caused by:

- high variety of vehicle servicing technologies (determined by variety of characteristics of the cars being serviced, variety of defects and damages, etc.);
- high differentiation of customer requirements;
- information uncertainty about the actual technical condition of the car;
- strong limitation of acceptable cost of diagnostic and repair work;
- low investment in new service technologies.

Solving the above-mentioned problems depends on the specificity of vehicle service station supply systems. In case of:

- decentralized system (so-called single-layer supply system), customer service in workshops (micro service companies) is carried out with direct purchase of parts in retail stores;
- centralized (so-called multi-layered, closed supply system), serviced is carried out by affiliated authorized car service companies of one manufacturer;
- dispersed system (so-called open network of independent auto-service centers), service within the network of independent auto-service centers connected into one whole.

From the point of view of customer service in the above supply systems, it is necessary to analyze factors increasing risk of mistake in service companies and to understand mechanism of competition in the auto service market and its impact on the quality of customer service. Together with development of automotive market, the information support in decisions making is gaining in importance. This is mainly due to fact that [34]:

- conclusions from the analysis of outdated information become obsolete and even bring negative effects – opposite to expected;
- growing openness of service companies' networks causes higher dispersion of information, which in turn complicates its collection, analysis and use;
- economic globalization contributes to the entry of new players into the automotive market preferring an offensive competition, which results in the emergence of information asymmetry.

According to the authors, the servicing of repair workshops should take into account decision-making approaches used in the national auto-service for the organization of supply chain of repair materials in the relationship "*customer – service company – spare parts manufacturer*". On the other hand, decision-making models in this respect should include at least one of the levels of multi-level hierarchy of the national diagnostic and repair network formed by micro, small and large service companies.

## 3. Literature review

Logistics requirements for spare parts supply differ in many respects, which results in different approaches to the selection of research methods. There is no common view on developing a unified approach to this issue. This is due to the fact that [21]:

- spectrum of services provided in auto service segment is generally very wide,
- demand for spare parts is often sporadic, and fluctuations in this demand make difficult anticipating the needs of both the range and number of parts and accessories needed,
- too low availability of spare parts stocks can lead to increases in their prices or delays in accident damage settlement, after-damage repairs, etc.,
- too high stocks of spare parts and accessories can lead to significant financial losses resulting from storage costs.

The problem of organization of logistics chains in supply and recovery logistics in the area of parts and product maintenance has been of interest to scientists for many years. In 1967, issues being the basis for today's logistics in the spare parts supply were presented in [48]. At the same time, the author of [14] noticed the need to set two directions of after-sales activity in the automotive market: servicing of new cars purchased from the manufacturer and withdrawn from service for reasons attributable to the producer, and servicing of used car [23]. In the 70-80s, logistics used to service used cars was associated exclusively with recycling, while car repair problems were considered secondary [15]. The analysis of literature in this area allows for conclusion that publication [41] dealing with the logistical support for vehicles service processes was a summary of that time achievements. This publication can be considered the first to highlight the link between reverse logistics with diagnostic and repair activities. In recent years, researchers emphasize the role of controlling spare parts inventory as one of the most important factors affecting service activities [24, 54].

The need for a broader study of the role of information dimension in organization and implementation of logistics chains supplying service stations with repair materials and the use of IT technology in this segment of logistics is described in [36]. Despite the availability of such technologies and their reputation of effective tools increasing effectiveness of supply chain management, the discussion of their implementation boils down to assessing the availability of input information needed to supply new and recovery parts [19, 42] and optimizing related costs and revenues [52]. The results of available literature analysis show some deficiencies in the discussion on the role of information in improving processes of supplying motor vehicle service stations.

Elements of such analysis appear together with continuous increase of car fleet management system importance, which largely relates to planning of repair, modernization and replacement processes in terms of exploitation [46]. Problems of commercial using of motor vehicles and resulting renewal conditions have a significant impact on models of supply chains [51], which are renewal systems restoring readiness to vehicles [28]. Fitting this renewal system into spare parts supply chains was discussed, among others in works [30] and [31].

To analyse the condition and development trends of the multi-segment vehicle service market, a review of selected publications summarizing achievements in this subject was carried out. Particular attention was paid to the analysis of logistics models for the supply of goods (Fig. 1). Publications cited in the Web of Science (Core Collection) and Scopus databases were examined.

In recent decades, various attempts have been made to solve the problem of modelling the process of servicing motor vehicles. Authors focused on two important issues; support for decision-making process and study of relationship between "*credibility of forecasts for demand for goods and accuracy of decisions about their production, storage and delivery.*" The latter direction was generally focused on forecasts of sporadic changes in demand for goods, including spare parts; unstable demand structure for this product and seeking for ways to mitigate the risk of supply breakdown due to information uncertainty (Table 1). Both classic models were analysed in the research, including models oriented on the use of SCM tools [6] as well as integrated models of artificial neural networks [17].

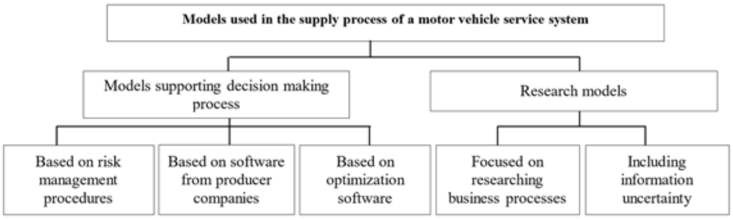


*Fig. 1. Classification of models analysed by literature review*

*Source: Own study.*

It was found that authors of these and other publications share a desire to obtain effective ways to overcome problems of supply chains organization and management, to develop effective models for distribution of goods to warehouses or network of stores [53]. The analysis of national publications shows that genetic algorithms [16] can be used in solving traveling salesman problem [2] or selection of resources for tasks [32].

Existing knowledge gaps in foundations of supply processes of automotive vehicle service stations contribute to mistakes in planning and managing supply chains and, as a consequence, to the low efficiency of the entire automotive logistics system. Therefore, authors attempted to solve several problems, namely structuring the Polish market of vehicles servicing and development of research tool related to ASRIM model, which is a modification of the ARIMA model and enables forecasting the flow of goods in conditions of information uncertainty. To use this model in the realities of domestic market, original models adapted to multi-criteria optimization have been proposed. These models, apart from minimizing the risk of ordering unnecessary or mismatched spare parts, also seek for minimum cost of supplying spare parts. The model assumes possible choosing of the right supplier, takes into account non-linear dynamics of studied phenomena and complexity of supplying motor vehicle service stations [25, 26, 29]. Aiming to reach the goal, authors decided to use an algorithm basing on Artificial Neural Networks (ANN) for obtaining solutions.

## 4. Decision models for supplying vehicle service stations with spare parts

### 4.1. Assumptions for building decision models

Results of literature analysis revealed the lack of compact concept for defining decision models for supply of spare parts to vehicle service segment, especially in the conditions of increasing meaning of fleet management.

There are two major problems in the car service market:

1) division of this automotive market segment into various sectors;
2) lack of effective supply chain models dominating in these market sectors.

Using so-called Low Hanging Fruit (LHF) rule, which means choosing the easiest to reach good solution, authors point out that auto service segment of automotive market can be divided into three sectors:

*Table 1. List of results of testing models used in goods delivery process*

| | | |
|---|---|---|
| **Models based on risk management procedures** | | |
| Wu T. et.al, 2006 [55] | PHA/AHP - based model | Model introduces two-stage assessment of supply risk. At the first stage, a PHA (*Preliminary Hazard Analysis*) is carried out to eliminate high risk suppliers. Other suppliers undergo the second stage of analytical hierarchy assessment. The scope of the model is limited to testing supplies as a one-level process. |
| Heckmann I., 2016 [18] | FTA-based model | The model is built on FTA (*Fault Tree Analyses*) method for analysing manifestations of individual threats for timeliness of deliveries. The possibility of common causes of unplanned interruptions in supplies is not taken into account. |
| **Software-based models for obtaining optimal solutions** | | |
| Du F., 2008 [11] | Pareto-based model | Model of two-criterion optimization according to minimizing the overall costs of vehicle service and minimizing delays in diagnostics and repair. |
| Frazzon E. M. et al., 2014 [12] | MILP -based model | Model is focused on minimizing unplanned breaks in the logistics process of supplying vehicle service stations and maintaining their operating costs at an optimal level. The simulation is performed in accordance with the deterministic scenario and aims to acquire ways to improve procurement process by optimizing logistics tasks under economic and environmental efficiency. |
| **Models based on software from producer companies** | | |
| Ho C. et al., 2007 [20] | ERP-based model | Model was built to assess the costs of supply depending on effectiveness of supply chain implemented under cooperation of various companies cooperating within the three-layer ERP system (*Enterprise Resource Planning*). |
| Li SG, et al., 2008 [37] | EFNN –based model | Model is based on the assumption that while planning deliveries, the manager has reliable and complete information in financial, environmental and market aspects with an indication of cause and effect relationships. |
| **Dynamic models aimed at researching business processes** | | |
| Bidhandi H.M et.al, 2011 [8] | Stochastic approach – based model | The model developed to Original Equipment Manufacturer (*OEM*), and the procurement process is analysed only in terms of possible increase in operating costs as a consequence of reduced demand and/or efficiency of car production factories. |
| Ambe I., et al., 2011 [6] | Demand-driven model | Model does not consider random events detrimental to the stability of spare parts supply. As the only way to ensure continuity of supply process, the need to permanently replenish stock of these parts was pointed out in order to mitigate the consequences of emergency situations. |
| Deloitte Consulting, 2017 [10] | Scenario -based model | Model is based on information collected through expert interviews, experience of managers acquired through organization of previous deliveries, and/or based on information collected as part of status monitoring and historical databases. The assumption results in a lack of flexibility in information flows and incompleteness of results and limits proper assessment of SC resilience to risks. |
| **Models taking into account information uncertainty** | | |
| Kochak A., 2015 [33] | ANN-based model | Model is developed to examine relationship between "*reliability of forecasts for the demand for goods and the accuracy of decisions on their production and delivery*." Forecasting is based on a very simple regression model that assumes that demand for goods is a function of time. |
| Luksch, S., 2014 [38] | ASRIM- based model | Model takes into account uncertainty arising from the lack of complete and reliable information about spare parts suppliers (inbound suppliers). It does not include random threats at individual links in the supply chain. The need to use cause-effect relationships to reduce information uncertainty is declared. |
| He W., 2013 [17] | ANN-base model | Model develops forecasts for safe levels of stocks of goods. It has limited application because it does not specify the number of layers of nodes (some of them may be hidden) and the issue of optimizing network structure is not raised, which can result in erroneous conclusions. The need to use experience to eliminate wrong decisions is declared. |
| ANN - *Artificial Neural Networks*; ARIMA- *Autoregressive Integrated Models of Moving Averages*<br>ASRIM - *After Sales Risk Management*; ERP - *Enterprise Resource Planning*; FTA- *Fault Tree Analyses*<br>EFNN - *Enhanced Fuzzy Neural Network*, MADM- *Multi Attribute Decision-Making;*<br>MILP - *Mixed Integer Linear Programming*; SCM- *Supply Chain Management* | | |
| Source: Own study. | | |

*Table 2. Individual barriers of development of vehicle service stations in individual sectors.*

| **Barriers to reverse logistics development** | | **General** | | | **Partial** | | | **Local** | | | **Share (%)** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **S1** | **S2** | **S3** | **S1** | **S2** | **S3** | **S1** | **S2** | **S3** | **S1** | **S2** | **S3** |
| 1 | Lack of qualified personnel | 0,8 | 0,8 | 4,7 | 7,7 | 7,7 | 3,1 | 9,2 | 5,3 | 4,3 | 17,7 | 13,8 | 12,1 |
| 2 | Outdated business models | 0,3 | 0,2 | 3,2 | 2,1 | 0,6 | 0,7 | 6,0 | 8,1 | 0,2 | 8,4 | 8,9 | 4,1 |
| 3 | Lack of compatibility between technologies used and planned to be used | 0,4 | 0,9 | 0,7 | 1,9 | 3,1 | 2,8 | 3,0 | 2,8 | 4,1 | 5,3 | 6,8 | 7,6 |
| 4 | Too high cost of implementing innovations | 8,4 | 2,4 | 1,4 | 2,0 | 8,3 | 5,3 | 11,1 | 0,4 | 3,4 | 21,5 | 11,1 | 10,1 |
| 5 | No personal motivation | 2,2 | 7,9 | 12,9 | 5,0 | 7,1 | 4,1 | 8,1 | 3,2 | 2,2 | 15,3 | 18,2 | 19,2 |
| 6 | Outdated equipment | 0,1 | 0,0 | 0,1 | 2,0 | 0,7 | 3.7 | 9,3 | 6,2 | 8,3 | 11,4 | 6,9 | 12,1 |
| 7 | Information uncertainty in financial, environmental and market aspects | 12,3 | 15,3 | 20,1 | 4,2 | 17,2 | 11,1 | 3,9 | 1,8 | 3,6 | 20,4 | 34,3 | 34,8 |
| **Share (%)** | | **24,5** | **27,5** | **43,1** | **24,9** | **44,7** | **30,8** | **50,6** | **27,8** | **26.1** | **100** | **100** | **100** |

Own study based on: [34]

1. The first sector (S1) connects all vehicle service stations that carry out all orders regardless of technical condition of vehicle, its age or brand (LHF means acceptance of all orders). These stations use outdated or non-specialized equipment, have low efficiency and high involvement of repaired car owners in the supply of spare parts and other materials. This sector includes small, low-budget, non-affiliated and unauthorized workshops, which specialize mainly in vehicle mechanics, bodywork and painting, and charge a lower remuneration for services than authorized stations.
2. The second sector (S2) includes high-budget authorized service stations, for which LHF means servicing cars from one manufacturer, of any degree of complexity, using only original spare parts, networked with other stations of the same manufacturer. These stations offer a wide range of services, and their offer includes the sale of spare parts, which significantly speeds up repairs, have better equipment, e.g. diagnostic computers which facilitates the work of mechanics.
3. The third sector (S3) includes service companies that perform all types of maintenance services for all car brands using original spare parts and accessories, specializing in automotive electronics, non-invasive diagnostics, service and maintenance of air conditioning and other complex car systems. Such companies are usually authorized by several manufacturers and connected according to the Business-to-Business integrated (B2Bi) principle.

Table 2 presents main barriers limiting development of individual segments due to information uncertainty. In order to develop appropriate models of spare parts and accessories supply chains, some principles of choosing strategies for managing these chains presented by, among others, Lee, H. in the work [35] should be taken into account. According to the recommendations, the management strategy should:

- ensure minimum costs of sourcing and maintaining inventory at the minimum required level;
- take into account the fact that demand for spare parts is probabilistic due to seasonal inequality of service orders, regional demand discrepancies, etc.;
- eliminate errors in organization of supply chains as a source of financial losses proportional to the number of customers lost due to a deficit of spare parts or other repair materials.

Bearing the above in mind, authors proposed three models of material and spare parts flows developed on the basis of results of analysis of the national after-sales cars service system. Models tend to minimize the risk of wrong decisions on the base of information asymmetry and incomplete or outdated information, as the assessment criterion.

## 4.2. Supply chain model for the micro-segment of unauthorized vehicle service stations

### 4.2.1. Model assumptions

This segment of vehicle service stations includes micro companies, which are usually unauthorized independent entities. They employ 1-2 employees able to repair, on average, 2-3 cars during the working day. Clients decide to involve stations from this segment in repair work, if only few elements are replaced, most often in braking, electric or suspension systems, i.e. R&I (*Remove & Install*) or R&R (*Remove & Replace*) type repairs. If the immediate repair is required, the burden of finding and supplying spare parts often falls on customers who can order these parts online, e.g. using the iPARTS delivery system (express delivery).

The circulation of information between units of this segment has two modes:

1. slow mode, resulting from the need for in-depth analysis of the car condition, the choice of technology to diagnose possible fatigue faults, settling necessary formalities, etc.
2. fast mode, resulting from deadline stated in repair contract.

Decision making process is done at all stages of car repairs and can be described by an S-shaped relationship (Fig. 2).

This is connected with:

1. Slowing down the exchange of information used in decision-making process regarding the formalities related to repair and settlement, agreeing the date of repair, planning diagnostic and repair work, valuation of service costs, organization of spare parts supply, inference based on damage diagnostics. Source

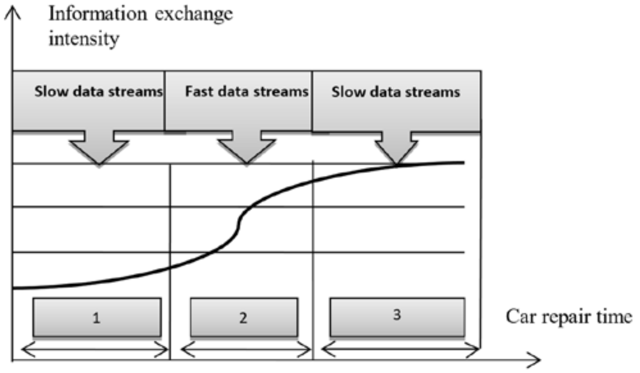


*Fig. 2. Dynamics of decision-making processes. Source: Own study*

of risk of incorrect decisions at this stage – the use of uncertain information from customers, suppliers, etc.

2. Fast exchange of information used in decision-making process during dismantling of used car parts, repairs and subsequent assembly of spare parts and accessories. Source of risk of incorrect decisions at this stage – internal human factor.
3. Slowing down the exchange of information used in decision-making process regarding the quality of repair, guarantee for repair, procedure to be followed in case of complaint. Source of risk of incorrect decisions at this stage – the use of unreliable test results, false information about the quality of supplied spare parts and accessories, etc.

### 4.2.2. Formal notation of a decision problem

The analysis of decision situation shows that the model is characterized by:

- unstable supply period, because customers have no insight into the spare parts and repair materials market,
- frequency of repair orders depends on seasonality, weather conditions, professionalism of previously performed inspections and diagnostic works,
- very high level of asymmetry of information exchanged by the parties in the relations "*Customer – Vehicle Service Station*" and "*Customer – Spare Parts Retailer*" (Fig. 3).

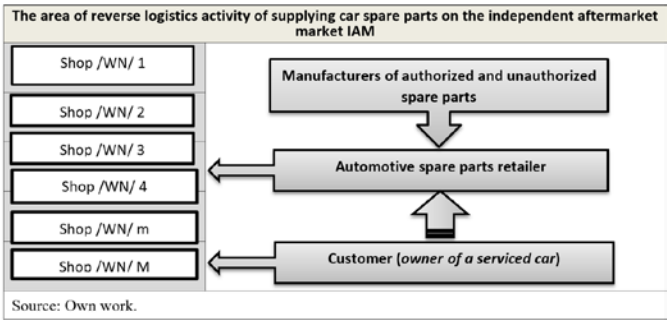


*Fig. 3. Logistic activity in the micro segment of unauthorized auto-service workshops.*
*Source: Own study*

Analysis of the situation from the decision maker point of view allows to define two states:

- ST-I – if decision-maker receives data on demand for services on ongoing basis, the level of information uncertainty may be assessed as. $U_i^o$ In this situation, the risk of making a faulty decision may be assessed as $R(U_i^o)$.
- ST-II – in this state it is possible that new information is not provided to decision maker for a time $\Delta t$. This increases the risk of making wrong decision, and the value of this increase is $U_{\Delta t}$.

The risk of making wrong decisions in each element of the supply chain, i.e. by a vehicle service representative, customer, manufacturer or automotive retailer can be described as:

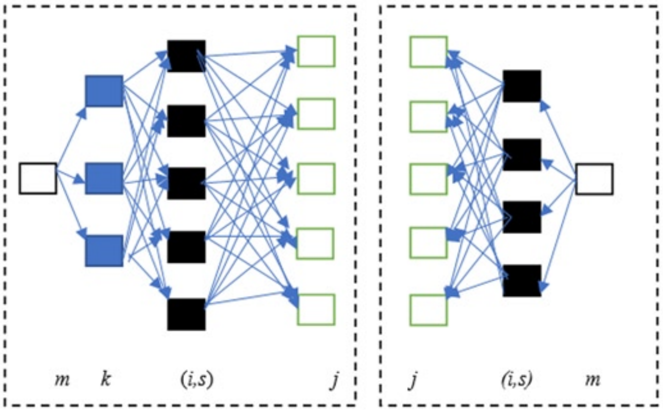
$$R(U_i^o + U_{\Delta t}) - R(U_i^o) = \Delta R_i^o \tag{1}$$

Equation (1) shows that $\Delta R_i^o$ is a measure of the risk of decisions based on outdated information. If decision-maker makes decisions on the base of information provided:

- *regularly*, if $R(U_{\Delta t}) \to 0$, then regardless of the category of information (aging of provided data is fast or not) the risk of making wrong decisions is acceptable;
- *irregularly*, if $R(U_{\Delta t}) >> R(U_i^o)$, then risk of making the wrong decision may exceed the level of acceptability.

As a result, $\Delta R_i^o \to 0$ is sought.

The flow of information in the model for micro-segment of unauthorized vehicle service stations is on two levels: workshop – customer and service station – automotive retailer. In the first case, customer organizes the process of supplying parts to the vehicle service station, in the second case customer does not participate in this process, but the vehicle service station orders goods itself. The information flow in the service station – customer relation can be represented as follows: *m* vehicle service station serves the client *k* and diagnoses failures in vehicle *j* (Fig. 4).



*vehicle service station – customer – vehicle service station – automotive retailer*

*Fig. 4. Information flow graph in the model of supply chain for the micro segment of unauthorized vehicle service stations. Source: own study*

The risk of incorrect diagnosis of customer's vehicle damage issued by the vehicle service station *m* is taken as $\Delta R1^0(m,k)$. The customer purchasing missing part *i* in automotive retailer *s*, takes the risk of making a mistake in purchase defined as $\Delta R2^0(m,k)$. The risk of not matching the part bought to the vehicle can be defined as $\Delta R3^0((i,s),j)$. If the part purchased by customer does not match the car, vehicle service station buys it from customer and uses in other vehicles in accordance with known matching risk $\Delta R3^0((i,s),j)$. It is problematic to find such a flow of information between vehicle service station and client that the risk of vehicle repair failure resulting from incorrect information is minimal.

Considering the above, three types of model decision variables are introduces: X1 – information flow from the vehicle service station *m* to the customer *k*, Y1 – information flow between the customer *k* and the automotive retailer *s* offering part *i*, Z1 – information flow resulting from compliance of the part *i* with damaged vehicle *j* offered by automotive retailer *s*:

$$\mathbf{X}1=\left[x1(m,k): x1(m,k)\in\{0,1\}, m\in \boldsymbol{M}, k\in \boldsymbol{K}\right]$$

$$\mathbf{Y}1=\left[y1(k,s,i): y1(k,s,i)\in\{0,1\}, k\in \boldsymbol{K}\ , s\in \boldsymbol{S}, i\in \boldsymbol{I}\right]$$

$$\mathbf{Z}1=\left[z1((i,s),j): z1(i,j)\in\{0,1\}, i\in \boldsymbol{I}, s\in \boldsymbol{S}, j\in \boldsymbol{J}\right]$$

The criterion function minimizes the risk of wrong decisions by all customers supplying vehicle service station *m* with missing parts, i.e.

$$\forall m\in \boldsymbol{M}$$

$$F1(\mathbf{X}1,\mathbf{Y}1,\boldsymbol{Z}1)=\prod_{k\in\boldsymbol{K}} x1(m,k)\cdot \Delta R1^0(m,k)\cdot \prod_{k\in\boldsymbol{K}}\prod_{s\in\boldsymbol{S}}\prod_{i\in\boldsymbol{I}} y1(k,s,i)\cdot \Delta R2^0(k,(i,s))$$
$$\cdot\prod_{s\in\boldsymbol{S}}\prod_{i\in\boldsymbol{I}}\prod_{j\in\boldsymbol{J}} z1((i,s),j)\cdot \Delta R3^0((i,s),j)\rightarrow min \qquad (2)$$

The information flow in relation: vehicle service station – automotive retailer is as follows: the vehicle service station, after diagnosing damage in a vehicle, orders part in the automotive retailer. The risk of incorrect diagnosis and ordering of part *i* by vehicle service station *m* in automotive retailer *s* is $\Delta R4^0(m,i,s)$. The risk of not matching the part bought in a store with the vehicle can be defined as $\Delta R3^0((i,s),j)$.

In this case, two types of decision variables are defined: X2 – interpreted as the information flow from the vehicle service station *m* to automotive retailer *s* regarding the order of the part *i*, Z1 – variable specifying the flow of information resulting from matching part *i* for damaged vehicle *j* offered by automotive retailer *s* takes the same form as in the service station – customer relation.

$$\mathbf{X2} = [x2(m,i,s): x2(m,i,s)\in\{0,1\},\ m\in\boldsymbol{M}\ i\in\boldsymbol{I},\ s\in\boldsymbol{S}]$$

Criterion function minimizing the risk of wrong decisions made by vehicle service station *m* takes the form:

$$\forall m\in \boldsymbol{M}$$

$$F2(\mathbf{X}2,\boldsymbol{Z}1)=\prod_{i\in\boldsymbol{I}}\prod_{s\in\boldsymbol{S}} x2(m,i,s)\cdot \Delta R4^0(m,i,s)\cdot$$
$$\cdot\prod_{s\in\boldsymbol{S}}\prod_{i\in\boldsymbol{I}}\prod_{j\in\boldsymbol{J}} z1((i,s),j)\cdot \Delta R3^0((i,s),j)\rightarrow min \qquad (3)$$

## 4.3. Supply chain model for the micro-segment of authorized vehicle service stations

### 4.3.1. General thoughts

The supply chain model for the micro-segment of authorized vehicle service stations includes dealer centres, which are usually authorized subsidiaries connected in a distribution network of new cars manufactured by one manufacturer. They employ 3-5 employees, who can repair 4-6 cars on average during a business day. Having at their disposal specialized tools dedicated to specific car models and electronic diagnostics systems, they provide various types of maintenance services, among which, in addition to R&I and R&R they offer FEA (Front-End Alignment) repairs. Dealer centres are characterized by the possibility of using stocks accumulated in small warehouses being a functional part of such a vehicle service stations.

Manufacturers invest in warehouse facilities gathering up to several thousand spare parts. As a result, dealer centres can maintain repair capacity for earlier car models and respond faster to demand. Deliveries to national dealer centres are done 3-4 times a week. An example of such a system is the InterCars Group distribution system built on three levels: retailers, regional warehouses and central warehouse. Regardless of the standard structure, there is a "Service 24h" which can in emergency cases send spare parts on holidays [22].

For the micro-segment of authorized dealer centres, the main barrier is the uncertainty of information arising when one of the parties has more of it (e.g. a car manufacturer) than the other (e.g. a vehicle service manager) having so-called informative time-trouble. Because the right decision depends on the value of information (usefulness, timeliness, completeness and reliability), managers always strive to obtain additional information.

### 4.3.2. Formal description of decision problem

If the required repair materials are missing, there are two ways to deliver them to a vehicle service station (Fig. 5):

- delivery by the owner of a serviced car (negligible cases);
- ordering requiring planning the supply period and structure, depending on the warehouse safety stock. In order to minimize transport and delivery costs, even for short-term planning tasks, it is usually assumed to increase the stock of spare parts to the maximum.

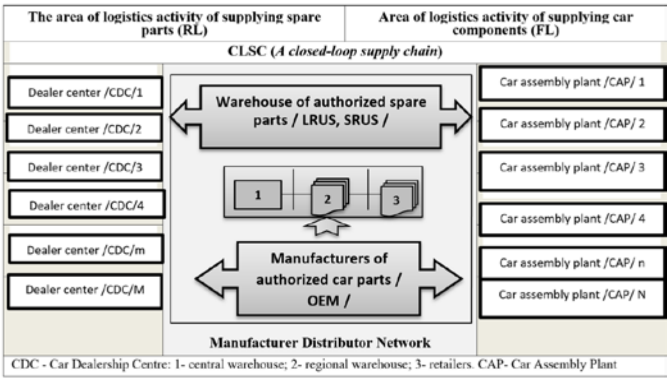


*Fig. 5. Logistic activity on the micro segment of authorized dealerships*

*Source: Own study*

The supply period is unstable due to asymmetry of information about the actual technical condition of car delivered for repair (even a detailed diagnosis does not always detect all defects) and unknown priorities of parts delivery by the distributor.

Most decision makers like dealership managers, stand out by their unwillingness to take risks. It was assumed that they manage to acquire additional information during time $\Delta t$ when making decisions, which reduces the level of uncertainty by $U_{\Delta t}$. Then:

- asymmetry of decision maker information decreases to a level $[U_i^{\mathrm{v}} - U_{\Delta t}]$.
- risk of decision in this case is:

$$R(U_i^y)-R(U_i^v-U_{\Delta t})=\Delta R_i^v \qquad (4)$$

where:

$U_i^{\mathrm{v}}$ – information uncertainty of decision makers after each *i*-th decision;

$R(U_i^v)$ – risk of taking i-th decision.

$\Delta R_i^v$ reflects the possible information asymmetry possessed by managers of authorized vehicle service stations. For this situation, decision variables defining information flow are defined: X2 – information flow between dealer centre *c* and customer *k*. The risk of misdiagnosis can be defined as $\Delta R5^0(c,k)$, Y2 – flow of information between the dealer centre *c* and supply warehouse *w*. Risk of incorrect ordering of part *i* is $\Delta R6^v(c,w,i)$; Z2 – information flow between the warehouse *w* and dealer centre *c* determining the risk of sending the wrong part *i* $\Delta R7^v(w,c,i)$.

The criterion function minimizing the risk of placing an order of the wrong part by a dealer centre takes the form:

$$\forall c \in \boldsymbol{C}$$

$$F2(\mathbf{X}2,\mathbf{Y}2,\boldsymbol{Z}2)=\prod_{k\in\boldsymbol{K}} x2(c,k)\cdot \Delta R5^{v}(c,k)$$

$$\cdot\prod_{w\in\boldsymbol{W}}\prod_{i\in\boldsymbol{I}} y2(c,w,i)\cdot \Delta R6^{v}(c,w,i)\cdot \prod_{w\in\boldsymbol{W}}\prod_{i\in\boldsymbol{I}} z2(w,c,i)\cdot \Delta R7^{v}(w,c,i)\rightarrow min \tag{5}$$

## 4.4. Supply chain model for the micro-segment of high-budget service centres

### 4.4.1. Model assumptions

One of the market trends is directing returns of sold production to specialized *Centralized Return Centre* instead of traditional distribution centres CDC. The reason for this is that most distribution centres are focused on selling and servicing new goods, rather than diagnostic and repair work. Therefore, the goal of CRC is to minimize the cost of repairs as a result of work in highly specialized workstations and the risk of buying a new product.

The analysed micro-segment includes large Car Return Centres – CRC. Such centres employ over 10 employees who, on average, make 7-10 car repairs during the working day. They have spare parts and car accessories and take an active part in the reverse logistics process. For over ten years, CRC have been implementing e-commerce procedures and operating in online mode. The offer of such online platforms includes up to a million spare parts and other materials needed for car repairs [39].

For the micro-segment of CRC, the main barrier is information uncertainty as a result of its distortion by dispersion during collection, transmission and processing in wide networks. The data distortion is directly proportional to the number of channels through which information is transmitted (e.g., the relationship between " vehicle service station – return centre" and "return centre – warehouse").

### 4.4.2. Formal notation of a decision problem

The model of services in the micro-segment is based on the maintaining critical levels of inventories needed to car service and sales-oriented inventory to third parties. The supply is made after reaching their minimum level. The planned supply period does not affect the time to service individual customers.

When cars are withdrawn in group from service as a result of detecting a factory defect, it is necessary to consider waiting time for delivery of the whole batch of spare parts, and supply period is unstable due to the asymmetry of information in relationship "*CRC – car manufacturer*" (Fig. 6).

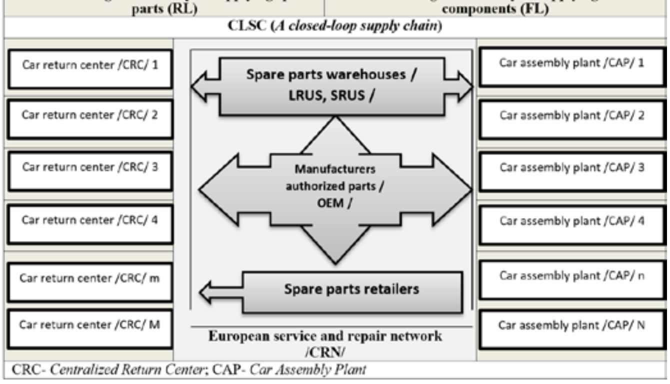


*Fig. 6. Logistic activity on the micro-segment of Return Centres*
*Source: own study.*

Situation analysis from the point of view of decision maker reveals two possible states. Let the decision maker be in a situation in which the information can be obtained directly from its source, and the number of these sources is limited. $U_i^d$ means the information uncertainty of the manager working in the CRC network, while $R(U_i^d)$ means the risk of making the wrong decision. It is also possible that decision-maker obtains information from various channels, which in turn obtain data from other sources. In this case, the processes of collecting, transmitting and processing data are burdened with the probability of information distortion. In this case, the risk of making the wrong decision can be assessed as:

$$R_i^d\left(U_i^d+\sum_{n=1}^{m}U_n^f\right)-R\left(U_i^d\right)=\Delta R_i^d \tag{6}$$

where:

$m$ – number of information sources,
$n$ – number of information channels in each of which it may be distorted.

$\Delta R_i^d$ reflects the possible distortion of information in the open CDC network.

In this case, four types of decision variables were defined. X3 – information flow between the return centre for defective vehicles and the warehouse. The risk associated with faulty order of the part $i$ is $\Delta R8^d(cr,w,i)$. Y3 – information flow between return centre for defective vehicles and spare parts retailers. Risk related to the faulty order of part $i$ is $\Delta R9^d(cr,s,i)$. Z3 – information flow between the warehouse and vehicle return centre. Risk of sending mismatched parts is $\Delta R10^d(w,cr,i)$. K4 – information flow between retailer and vehicle return centre. Risk of sending a mismatched part is $\Delta R11^d(s,cr,i)$.

The criterion function minimizes the risk of ordering a non-matching part by a return centre:

$$\forall cr \in \boldsymbol{CRC}$$

$$F3(\mathbf{X}3,\mathbf{Y}3,\boldsymbol{Z}3,\boldsymbol{K}3)=\prod_{w\in\boldsymbol{W}}\prod_{i\in\boldsymbol{I}} x3(cr,w,i)\cdot \Delta R8^{d}(cr,w,i)\cdot$$

$$\cdot\prod_{s\in\boldsymbol{S}}\prod_{i\in\boldsymbol{I}} y3(cr,s,i)\cdot \Delta R9^{d}(cr,s,i)$$

$$\cdot\prod_{w\in\boldsymbol{W}}\prod_{i\in\boldsymbol{I}} z3(w,cr,i)\cdot \Delta R10^{d}(w,cr,i)\cdot \prod_{s\in\boldsymbol{S}}\prod_{i\in\boldsymbol{I}} k3(s,cr,i)\cdot \Delta R11^{d}(s,cr,i)\rightarrow min \tag{7}$$

## 5. The risk minimization algorithm in supplying vehicle service stations with spare parts

### 5.1. General assumptions of the genetic algorithm

Solution of decision models developed in chapter 4. requires an appropriate optimization algorithm adequate to decision variables. The genetic algorithm is an iterative algorithm, so the generated solution improves solution with each passing to the next iteration. Each individual in population is assessed according to the adaptation function constructed exclusively for the problem. Selection process in genetic algorithm chooses best individuals (chromosomes) from the initial population for the next generation. The crossing process involves exchange of genetic material between two individuals, resulting in individuals added to the population of children. The mutation process involves swapping individual genes in the chromosome. The population of individuals consists of individual chromosomes that represent the solution to a given decision problem.

A simplified scheme of classic genetic algorithm is shown in Fig. 7.

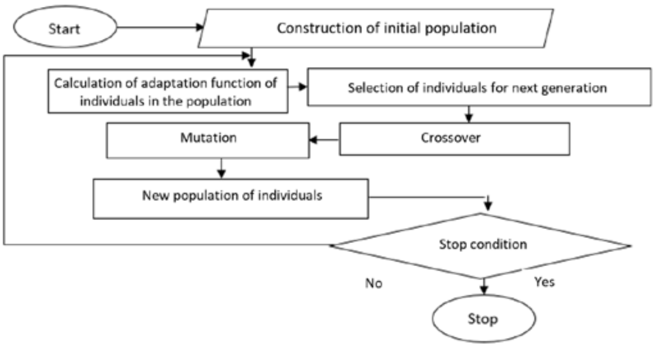


*Fig. 7. Diagram of a genetic algorithm*

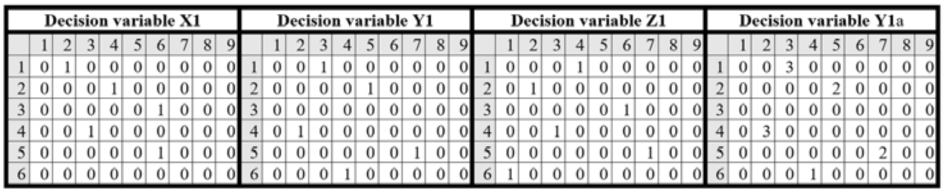
*Source: own research.*

## 5.2. Stages of algorithm construction

Stages of genetic algorithm construction are presented on the base of supply chain model for the micro-segment of unauthorized vehicle service stations. The algorithm stages can be presented as following: **Stage 1**. Determining the structure of input data. **Stage 2**. Determining the adaptation function. **Stage 3**. Constructing the reproduction process. **Stage 4**. Defining the crossing process. **Stage 5**. Determination of the mutation process.

Stages I-II are one-time stages at the beginning of the algorithm. Stages III-V are repeated a certain number of iterations until the stop condition is reached. The stop condition is a certain number of iterations. The assessment of individuals is carried out on the base of adaptation function, which covers criteria functions of individual models of information flow in supply chain.

Data structure processed by the algorithm is a matrix determining connections between individual supply network elements, as well as the number of parts ordered from individual suppliers. Structures present values taken by decision variables of the model of supply chain for the micro-segment of unauthorized vehicle service stations (decision variable X1 – information flow between service station (matrix rows) and the customer (matrix columns), decision variable Y1 – information flow between customer (matrix rows) and retailer (matrix columns), decision variable Z1 – matching parts (matrix rows) to a damaged vehicle (matrix columns)). The decision variable Y1a specifies the purchase of a specific number of parts by a customer (matrix rows) in each automotive retailer (matrix columns). Each retailer offers a given part at a different price. It is problematic to indicate retailer where a given part can be purchased at minimal costs. An example structure is shown in Fig. 8.



| Decision variable X1 | | | | | | | | | | Decision variable Y1 | | | | | | | | | | Decision variable Z1 | | | | | | | | | | Decision variable Y1a | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 3 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 2 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 |
| 3 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 0 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 5 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 5 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 5 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 |
| 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 6 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 6 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 6 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |

*Fig. 8. Matrix structure of the genetic algorithm*

*Source: own study.*

The adaptation function evaluates each matrix. To present the problem in a multi-criteria approach, the adaptation function takes the following form:

$$Fdop = \frac{F1(\mathbf{X}1,\mathbf{Y}1,\boldsymbol{Z}1)}{F1\min(i)} + \frac{F(\mathbf{Y}1a)}{F\min(i)} \to min$$

where:

$F1(\mathbf{X}1,\mathbf{Y}1,\boldsymbol{Z}1)$ – function assessing the risk of error arising as a result of incorrect information flow,

$F(\mathbf{Y}1a)$ – cost of parts purchase,

$F1\min(i)$ – minimum value of the risk function selected from the whole population in a given iteration,

$F\min(i)$ – minimum value of the cost function selected from the whole population in a given iteration,

The reproduction (selection) involves duplication of matrixes in subsequent generations (iterations of algorithm) depending on the adaptation function of these structures. Roulette method basing on the selection of new population according to the probability distribution specified on the values of adaptation function is used for selection [16].

Crossover of chromosomes (matrixes) is based on random selection of a decision variable for which the crossover process will be carried out and random selection of matrix substructure which will be exchanged between two chromosomes. In case of drawing the variable Y1, crossover must occur simultaneously for variables Y1 and Y1a.

The mutation involves random selection of a decision variable and random gene within it to be changed. In case of binary decision variables, the change is from 0 to 1 or 1 to 0, while for integer variable the change means an increase in the gene value by 1 or decrease by 1.

The final goal of the algorithm after a certain number of iterations is to determine such values of decision variables that simultaneously affect the minimization of risk and the cost of ordering specific parts for automotive service stations.

## 6. Conclusions

The paper presents theoretical basis for development of decision models of supply chains supplying vehicle service stations with parts. Models base on uncertain information associated with various random situations, risk of incorrect diagnosis of damaged vehicle and, as a consequence, purchase of a mismatched part or a risk of a mistaken part released by an automotive retailer. An original optimization algorithm has been proposed to minimize the risks associated with parts purchase.

In case of low demand for maintenance services and uncertainty of its growth in short term, the effectiveness of logistic support is the only competitive advantage of service workshops. The ability to rationalize costs and efficiency of information activities are two components of this efficiency.

However, in case of high demand for maintenance services due to seasonal reasons or modernizations planned on large scale, one of the logistics tasks is to design supply chains of spare parts and other repair materials. Such deliveries due to high demand must be carried out according to the maximum efficiency principle. Car service stations in this situation become highly profitable when servicing corporate clients. It should be noted that in case of high demand for maintenance services and certainty of long-term upward trend, the level of uncertainty in relation to the possibility of supplying spare parts according to the JIT principle increases. This condition is a risk of failure to carry out renovation work on time and not meeting customer expectations.

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