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Heuristic Supply Chain Optimization of Networked Maintenance Companies

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Abstract

This paper considers the problem of networked maintenance companies and the connected purchasing processes. Today's successful operation of companies views maintenance as a high priority to ensure maximum utilisation of resources. In this article, a mathematical model is first developed to formulate the problem of finding the optimal make-or-buy solution for complex spare part production. The model seeks the optimal proportion of in-house and outsourced productions, as well as the order quantity so as to minimize the total costs while taking into account order limits. Next, we demonstrate an enhanced harmony search algorithm dealing with multi-objective supply chain model to find the optimum make-or-buy solution of a given maintenance related supply chain problem. We also discuss the sensibility analysis of the heuristic optimisation method and propose optimal process parameters for a high convergence. Numerical results demonstrate how the proposed model supports the make-or-buy decision and helps to reduce the total costs while keeping high availability to fulfil maintenance tasks.

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Keywords: harmony search; logistics; maintenance; optimisation; supply chain

1. Introduction

Over the last few years, scientists have increasingly focused on the optimal design and control of networked production and service enterprises. The networked maintenance is a very important part of this research field, because of the high complexity of the connected logistic systems and processes [1,2,3]. This is a result of increasing pressure upon production and service companies to meet customer's demands and achieve the availability of their services. This section is focusing on the context and motivation of this research work, shows the related results based on the

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available literature and define the contribution of the authors.

1.1. Context and motivation

In our previous works, we have developed optimization models and methods for optimal support of make-or-buy problems of assembly companies. The present study is motivated by the below mentioned literature review which shows, that to the best of our knowledge there is no models and methods to optimize networked maintenance systems from the point of view make-or-buy decision. The make-or-buy optimization of networked maintenance processes (MoBNMP) supports the major logistic tasks, such as reliability, cost efficiency and helps to increase the transparency of the connected supply chain. The used methods are heuristic, because of the complexity of the problem. What influences the development of networked logistic processes? The increased number of products, the diversity of customer's demands, the possibility for horizontal and vertical cooperation, the up-to-date ITC technologies and last but not at least the outsourcing. The context of the research work is depicted in Fig. 1.

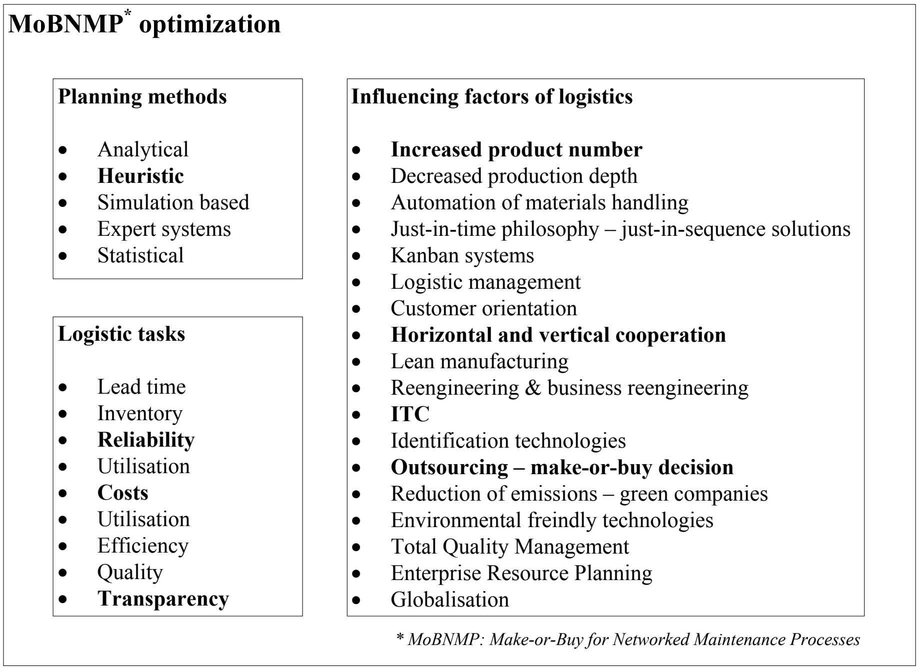

Fig. 1. Relationship of MoBNMP optimization to the planning methods, general logistic tasks and influencing factors of logistics.

The design of logistic processes aims the followings: increasing of utilization of production and logistic resources; decreasing lead time; decreasing of stocks; decreasing of technology and logistic related costs; increasing flexibility and transparency; increasing quality of products and processes; decreasing environmental pollution; integration of the maintenance processes into the controlling and information system of the enterprise.

1.2. Literature review

Within the frame of this section we give a short overview of related scientific papers. There are two main streams of literature. The first main stream is dealing with maintenance systems and the second one is focusing on the make-or-buy decision. The maintenance of resources in production and service companies is integrated into the logistic processes [4,5]. This integration is especially important in the case of networked maintenance systems, where resources to be maintained have wide range geographical locations. There are different research works, that describe different analytical, heuristic and simulation based methods to plan and control the maintenance processes. Aerospace maintenance is a very typical area of this problem, because operation and support costs represent the main part of the total life cycle costs flying vehicles. A virtual environment for operation process simulation makes it possible to support the maintenance process design from the point of view logistics [6]. Another special networked maintenance application is the maintenance of highway infrastructure. Due to the shrinking budget the cost efficiency is very important. One possible way to find a cost efficient process is the solution of resource effectiveness maximization problem [7], which is based on the Debreu method for calculation of the coefficient of resource utilization [8]. The networked maintenance companies need a global support environment with up-to-date IT solutions [9]; one of these IT solutions is the eMaintenance, which integrates the logistic processes of maintenance operations and ICT perspectives [10]. The operation of networking maintenance companies and maintenance processes is mostly provided by logistic companies or logistic service centers. This realization of networked operations is very typical in the field of transportation fleet maintenance scheduling problems [11,12].

One of the first basic tutorial works dealing with make-or-buy decision was written almost 30 years ago [13]. The make-or-buy decision is based on the purchasing behavior of the production companies [14], but a wide range of effects have to be taken into consideration [15,16]. The uncertainty plays an important role in the process of production; therefore stochastic effects must be taken into consideration [17].

The make-or-buy decision can be represented not only in the field of production but also in the processes of service companies. Some author proposes models and algorithms to solve the make-or-buy problems of service processes. The service capacity of production companies with after-sales services can be optimized by the aid of game theory [18]. By the aid of a fuzzy bi-criteria optimization model the make-or-buy decision of software system components can be solved [19]. The health service represents a special area of services, where instead of production depth we can speak about service depth and the availability of outsourced and in-house realized services has a significant importance.

1.3. Paper contribution

The research methodology includes four steps: problem definition, mathematical modeling of the problem, numerical experiments, sensitivity analysis. The review of the relevant literature revealed, that the analysis of purchasing systems of networked maintenance processes makes it possible to increase the efficiency of the whole system. To the best of our knowledge, there is no existing paper that investigates the spare part purchasing problem from the point of view make-or-buy decision. We propose a model and a solution method, which makes it possible to find the best suppliers and determine the best purchasing value for each required complex spare part.

1.4. Paper outline

Section 2 describes the supply chain problem including the mathematical model developed to formulate this large scale logistic problem. Section 3 presents the short description of the applied harmony search algorithm, the numerical result of a scenario experiment and the sensitivity analysis of the process parameters of the modified harmony search algorithm. Section 4 concludes the paper.

2. Problem description and formulation

The increased complexity of production and service processes led to the high number and diversity of resources. The availability and reliability of these resources need an up-to-date maintenance system. The required complex spare parts of maintenance processes represents an important part of logistic costs, therefore it is very important to optimize the supply chain of networked companies from the point of view make-or-buy decision to decrease the production and purchasing costs. The problem can be analyzed either from the point of view maintenance networks or from the point of view supply chain optimization with focus on make-or-buy decision.

2.1. Networked maintenance

The modeling of the make-or-buy decision of networked maintenance system is based on the multilevel supply chain. As Fig. 2. demonstrates, the system includes the following components:

- Suppliers are producing components for the complex spare parts required by the maintenance companies;
- Virtual logistic center as 3PL partner plan and control the supply chain of the networked maintenance system; it is responsible for the organization of purchasing, production and distribution processes of the whole system;
- Maintenance companies have the core competencies, they are responsible for the maintenance processes and the explanation of the required complex spare parts for each maintenance task;
- Maintenance location, where the maintenance processes must be realized.

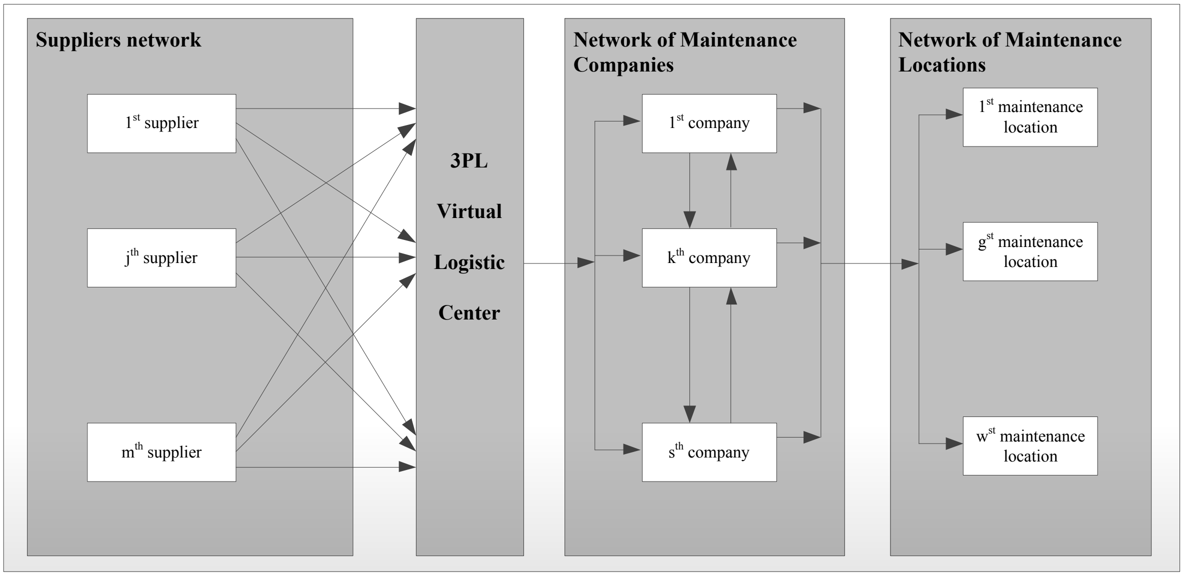

Fig. 2. Model of supply chain of networked maintenance process.

2.2. Make-or-buy decision

Companies with limited technological, human and logistic resources are not able to produce all required components, and they try to outsource some of them. The outsourcing of production of some components is a quite difficult question because of the high number of influencing factors: inventory, throughput time, independence of the company from other manufacturers, available product and technological know-how of the contract manufacturers, available resources and stock, achievability of quality specifications, costs. These influencing factors are the constraints of a make or buy decision. Make or buy decision is a very important part of just in time production. By the aid of a correct make or buy decision, it is possible to increase the return of investment by the aid of reducing the inventory and the required resources. These days the optimization of production depths is involved into lean processes of companies. The production depth of 0% means that the company does not have own production or assembly, so it is a handling company. The production depth of 100% means that the company has a value making chain, which makes it possible to produce their products independent from other suppliers. The production depth is also called as real net output ratio. The average depth of production is strongly decreased: the German automotive industry has got a production depth about 50% in the late 80s. The E-class Mercedes cars have got a production depth of 38% and this value of Porsche Leipzig is about 10% (Porsche 911 and Boxter 20%, Cayenne 10%). The production depth influences the structure of the supplier industry, which is definitely increasing.

2.3. Mathematical model

The mathematical model describes the networked maintenance supply chain. The equations establish relationships between costs, values of components, suppliers, maintenance companies and 3PL partners. Table 1. shows the explanations for used notations and indices.

Table 1. Explanations for the used notations and indices.

Notation	Explanations for the notations
$r_{i,j}^{B}$	Production capacity of the j-th supplier from the i-th component
$r_{i,k}^{M}$	Production capacity of the k-th company from the i-th component
$y_{i,j,k}^{B}$	Availability of the j-th supplier by the k-th maintenance company in the case of the i-th component
$y_{i,k,f}^{M}$	Availability of the k-th maintenance company by the f-th maintenance company in the case of the i-th component
$c_{i,k,f}^{M}$	Cost of the in-house production of the i-th component by the k-th maintenance company for the f-th maintenance company
$c_{i,j,k}^{B}$	Purchasing cost of the i-th component by the j-th maintenance company from the k-th supplier
$x_{i,k,f}^{M}$	Element of the solution matrix for in-house production; the amount of the i-th component produced by the k-th maintenance company for the f-th maintenance company
$x_{i,j,k}^{B}$	Element of the solution matrix for purchasing; the amount of the i-th component purchased from the j-th supplier for the k-th maintenance company
i	Component identifier
j	Supplier identifier
k,f	Identifier of the maintenance company

In the case of the networked maintenance system supported by 3PL depicted in Fig. 2., the required components can be purchased either from m different suppliers or from s different manufacturing companies. The production capacities of the suppliers and the own production companies are given:

$$R^{B}=\left[r_{i,j}^{B}\right] \text{ and } R^{M}=\left[r_{i,k}^{M}\right] \tag{1}$$

It is possible to define three typical make-or-buy decisions depending on the available capacities of the suppliers and maintenance companies. The make-or-buy decision of the i-th component will lead to a clear in-house production in the following case:

$$q_{i,k} \le \sum_{k=1}^{s} r_{i,k}^{M} \text{ and } \sum_{j=1}^{m} r_{i,j}^{B} = 0\,. \tag{2}$$

The make-or-buy decision of the i-th component will lead to a clear outsourcing in the following case:

$$\sum_{k=1}^{s} q_{i,k} \le \sum_{j=1}^{m} r_{i,j}^{B} \text{ and } \sum_{j=1}^{m} r_{i,k}^{M} = 0\,. \tag{3}$$

The make-or-buy decision of the i-th component will lead to a mixed purchasing solution in the following case. In this scenario the purchasing of the required component from another maintenance companies is a simple make decision.

$$\sum_{k=1}^{s} q_{i,k} > \sum_{j=1}^{m} \left(r_{i,j}^{B} + r_{i,k}^{M} \right) \text{ and } \sum_{k=1}^{s} q_{i,k} < \sum_{j=1}^{m} r_{i,j}^{B} \text{ and } \sum_{k=1}^{s} q_{i,k} < \sum_{k=1}^{s} r_{i,k}^{M} . \tag{4}$$

Let us introduce the main constraints. The first constraint defines, that the required amount of each component must be purchased or produced:

$$\sum_{k=1}^{s} \sum_{f=1}^{s} x_{i,k,f}^{M} + \sum_{j=1}^{m} \sum_{k=1}^{s} x_{i,j,k}^{B} = q_{i,k} . \tag{5}$$

The second constraint defines, that components can be purchased only from dedicated suppliers:

$$y_{i,j,k}^{B} = 0 \rightarrow x_{i,j,k}^{B} = 0 . \tag{6}$$

The objective function can be formulated as

$$\sum_{i=1}^{n} \sum_{k=1}^{s} \sum_{f=1}^{s} \left(x_{i,k,f}^{M} \cdot c_{i,k,f}^{M} \cdot y_{i,k,f}^{M} \right) + \sum_{i=1}^{n} \sum_{j=1}^{m} \sum_{k=1}^{s} \left(x_{i,j,k}^{B} \cdot c_{i,j,k}^{B} \cdot y_{i,j,k}^{B} \right) \rightarrow \min . \tag{7}$$

The above mentioned model can be solved by metaheuristics as demonstrated below.

3. Numerical experiments

This section describes the chosen optimization method, demonstrates a scenario experiment, within the frame of which the MATLAB based application is evaluated. The results of a sensitivity analysis are introduced. The aim of this sensitivity analysis is to validate the experiment results of the scenario by the aid of finding the best process parameters of the algorithm.

3.1. Harmony search algorithm

In 2001 Zong Woo Geem published an algorithm, inspired by musicians [20,21]. It's called Harmony Search algorithm, which can be used to optimize different NP-hard problems as other metaheuristics [22]. The algorithm is part of the phenomenon-mimicking algorithm, also known as metaheuristic algorithm in computer science and operations research. The algorithm is very special because it doesn't require initial values. The Harmony Search combine normal and random natural phenomena, like the other metaheuristic algorithms, in this case it is based on the harmony of the music. The HS algorithm consists of 5 steps:

- We must define the problem, and put in the algorithm parameters.
- We have to fill (create) the Harmony Memory matrix.
- We need to create (improvise) a new solution.
- If the new solution is better than the worst solution in the HM, then it must be replaced.
- Repeat the 3rd and 4th step until we get the perfect harmony.

In the algorithm the variables represents the musicians, the note is a value, the play is when we generate new solutions and the perfect harmony is the global optimum. Every musician has special improvisation techniques when they play their parts, and modify the sound of the instrument to create a better harmony with the other instruments. In the algorithm there are three major techniques to "improvise" new solutions. The Harmony Memory Considering Rate (HMCR) and Pitch Adjustment Rate (PAR) helps us to decide which technique is more useful in a problem, and we can set it like probability variables. There are two more important values. The Harmony Memory Size (HMS) decides, how many solutions we keep, and the bandwidth (bw) tells us how much we can modify a variable. Techniques to create new solutions: we create a totally random solution just like when we fill the HS matrix; every variable in the new solution gets a randomly chosen from another solution; just like the 2. technique, but we modify the value in some case. We can control the frequency of modification with the bandwidth.

3.2. Scenario experiment

Within the frame of this section we will describe a short scenario experiment, which is based on a quite simple supply chain with one singular supplier, 3 maintenance companies and 4 required compact spare parts assembled from 30 components. Some of the components are connected to several elements, like the 16th, 29th. In the next period we required the following main spare parts: 1. 250 units, 2. 75 units, 3.300 units, 4. 200 units. We want to know which elements we should make and buy to minimize the total costs of purchasing and production.

Table 2. The make-or-buy costs for each component.

Components	1	2	3	4	5	6	7	8	9	…	24	25	26	27	28	29	30
Buy costs [€]	42	99	39	92	6,5	23	24	7	30	…	8,2	3,9	7,1	1	2,3	2,2	1,4
Make costs [€]	7	7	3	5	1,4	2,5	2	7,8	3	…	8,8	3,2	8,2	0,7	1,8	1,8	1,7

The first step is to transform the assembly trees into an assembly matrix. The matrix is NxN quadratic matrix, where N is the number of the elements of the assembly trees. Then we need to collect the costs of the elements. Every component has a cost of buying, that shows, how much it will costs, if we buy it from external sources. It contains the elements price, transport, storage, waste and other costs. In the cost of buying column we give average costs of the element for a better overview. The cost of making represents, how much will it totally cost if we manufacture or assemble the elements ourselves. It contains real (material, energy, wages, protection, etc.) costs and fictional (moral, safety, speed, flexibility, know how, etc.) costs. The material cost mostly appears in the assembly trees leaves. After we create these matrixes, we have to put them into the program along with HMCR, PAR, bw, HMS and iteration numbers.

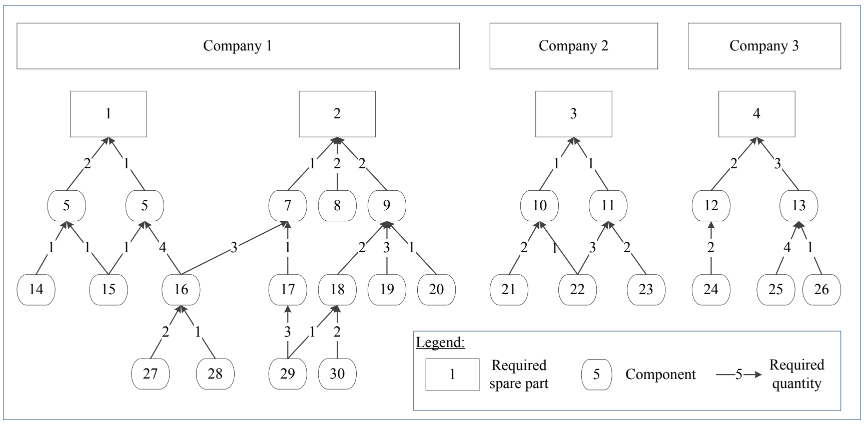

Fig. 3. Required complex spare parts of the three maintenance companies.

The termination criterion here is the iteration number, which determines how many new solutions the program has to create before it stops. If the result does not meet our expectations, the easiest way to increase the iteration number or we should make a sensitivity analysis. The running process can be traced in Fig. 3.

Table 3. The results of make-or-buy decision for each components of required complex spare parts; total parts needed.

Components	1	2	3	4	5	6	7	8	…	24	25	26	27	28	29	30
Make/Buy/Don't do anything	M	M	M	D	M	M	M	B		D	D	D	D	D	M	B
TPN	250	75	300	0	500	250	75	150		600	0	0	0	0	525	600

The main part of the program can calculate the cost of any variation. It does this based on the following algorithm:

$$TC_i^B = C_i^B \cdot (1 - X_i) \cdot X_p \ \ and \ \ TC_i^M = \left(C_i^M + \sum_{j=1}^{o} \left(C_{i,j}^M \cdot N_{i,j} \right) \right) \cdot X_i \cdot X_p \tag{8}$$

$$C = \sum_{k=1}^{u} TC_k^B \cdot (1 - X_k) + TC_k^M \cdot X_k \tag{9}$$

The explanations of the used notation of (8-9) are depicted in Table 4.

Table 4. Explanations for the used notations in the algorithm.

Notation	Explanations for the notations
TC_i^B, TC_i^M	External costs of the components and the costs of the components of complex spare parts to build from the basics
C_i^B, C_i^M	The costs of make and buy decisions
X_i, X_k	The solution variable of the component
X_p	The predecessor variable of the complex spare part component

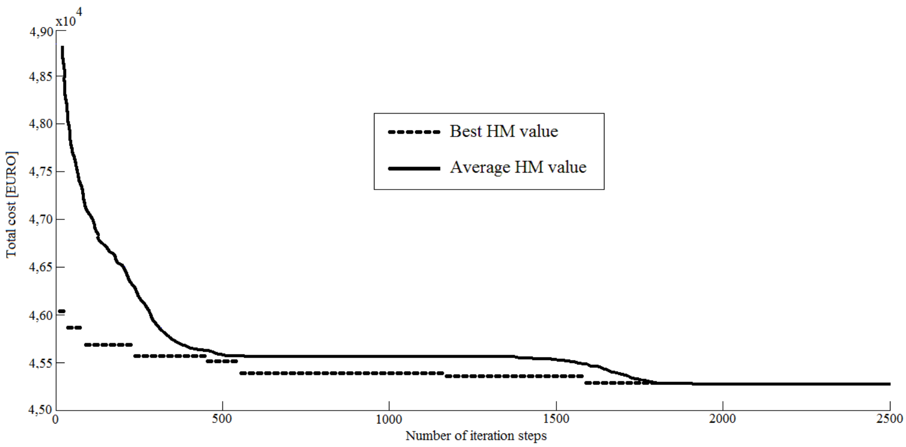

Fig. 3. Required complex spare parts of the three maintenance companies.

3.3. Sensibility analysis of the optimization algorithm

Sensibility analysis of heuristic optimization algorithms is very important part of the validation. The aim of the sensibility analysis is to find the best algorithm parameters for which the results of the described mathematical model meet the optimum criterion. With a proper setting of the HMCR, PAR, bw and HMS we can make the optimizing progress faster and more accurate. In the analysis we examine all major variables in the same settings within certain limits. We use the example task for the test. We watch the iteration number until the Harmony Memory's average reach the optimal value. Table 5. demonstrates the effect of harmony memory considering rate on the required number of iteration steps to find a predefined lower limit of the possible solutions. The best rate of choosing a possible solution vector from the harmony memory matrix is in the case of the above mentioned scenario 70%. This value is generally from 70% to 90 %.

Table 5. Effect of harmony memory considering rate.

HMCR	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9
Iteration number	8860	5642	2538	2455	1461	1572	1415	1550	1739
Difference	100	57	15	14	1	2	0	2	4

Table 6. shows the influence effect of the pitch adjustment rate. The best rate of choosing a neighboring value of the solution is 30% in the case of the scenario, which is correct, because the value of the pitch adjustment rate varies from 10% to 50 %.

Table 6. Effect of pitch adjustment rate.

PAR	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9
Iteration number	1334	1213	1086	1482	1412	1435	1472	2011	2968
Difference	13	7	0	15	17	19	21	49	100

Table 7. illustrates the effect of the bandwidth on the convergence speed of the algorithm. The best value of maximum change in pitch adjustment is 0,1 times the allowed range. The literature describes a general range between 0,01 and 0,001 times of the allowed range, but it is not a "must be", as this sensitivity analysis shows [2]. Depending on the search space special parameter set should be required to minimize the computation time and maximize the optimum criterion.

Table 7. Effect of bandwidth.

Bandwidth	0,01	0,05	0,1	0,2	0,3	0,5	0,75	1,00	2,50
Iteration number	2683	1367	1237	1422	1478	1547	1634	2862	3906
Difference	54	5	0	7	9	12	15	61	100

Table 8. demonstrates the influence of the harmony memory size on the required iteration steps. The best harmony memory size is 50 in the case of the above mentioned scenario.

Table 8. Effect of harmony memory matrix size.

HMS	1	5	10	30	50	75	100	200	500
Iteration number	2480	3772	2607	1516	1211	1789	2066	4687	10730
Difference	13	27	15	3	0	6	9	37	100

As a result of the sensibility analysis we can say, that the process parameters of the algorithm influence the convergence speed and required computation time or steps. The optimal process parameters depend on the problem and they must be tailored for each scenario.

4. Conclusions and future work

The optimal design and control of maintenance systems is a quite difficult problem, especially from the point of view spare part purchasing. The harmony search based methodology developed herein has allowed modeling and optimizing the purchasing process of networked maintenance processes from the point of view make-or-buy decision. The model output highlighted that in order to fulfill the maintenance needs the reliability. A key advantage of the optimization of maintenance supply chain is the ability to decrease the purchasing and production costs of the whole supply chain. For future research, a classification of the different types of networked maintenance processes will be made. Also the stochastic effects of parameters will be studied.

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