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Methods of supplier selection for producers of electric and electronic equipment

***Abstract**. Two methods supporting selection of suppliers for producers of electric and electronic equipment have been presented. After the initial, multi-criteria supplier selection, the problem of mathematical programming is solved which takes into consideration the cost criterion. One of the methods for this is search for optimum solutions, the other is called relaxation heuristics. These methods allow construction of schedules for product deliveries. The results of calculation experiments have been included.*

***Streszczenie.** Przedstawiono dwie metody wspomagające wybór dostawców dla producentów sprzętu elektrycznego i elektronicznego. Po wstępnej, wielokryterialnej selekcji dostawców rozwiązywane jest zadanie programowania matematycznego, uwzględniające kryterium kosztowe. Jedna z metod przeznaczona jest do poszukiwania rozwiązań optymalnych a druga jest heurystyką relaksacyjną. Metody umożliwiają budowę harmonogramów dostaw produktów. Zamieszczono wyniki eksperymentów obliczeniowych. (**Metody selekcji dostawców dla producentów sprzętu elektrycznego i elektronicznego**)*

Keywords: Integer programming, Supply network, Scheduling, Heuristics.
Słowa kluczowe: programowanie całkowitoliczbowe, sieci dostaw, szeregowanie, heurystyki.

1. Introduction

A major part of the plants which produce electric equipment or electronic devices function within supply networks. These plants have demands for various types of components and electronic circuits. Recipients of these components are at the same time suppliers of semi-finished products or finished devices for other companies of end recipients. Production is dependent on quality of service performed by other companies. Competitiveness of the market, pursuit after timely execution of orders and avoiding contractual indemnities make producers of electric and electronic equipment apply multiple criteria in supplier selection. Supplier are needed who at the same time meet the following conditions:

- They offer products at relatively low costs;
- They employ advanced technologies;
- They have very good quality control of products;
- They feature high degree of reliability or proper execution of orders;
- Their products are different from others (e.g. with design, guarantee terms);
- They ensure regular and reliable deliveries with guaranteed penalties for delayed deliveries.

The above are only some factors significant in selection of suppliers who provide components for producers of electric and electronic equipment. Availability of means of transport and costs of the offered transport services are also taken into account in selection of suppliers. Many suppliers currently have their own means of transport or take advantage of services of other logistics operators. Social factors are also important, for example experience in cooperation with other companies, as well as supplier's willingness to meet additional requirements.

A number of publications are dedicated to the issue of production planning, for example [1, 2], while production planning using linear programming has been described in [3, 4]. Problems connected with supply chains management are presented in the works of [5, 6]. Application of integer programming for solving supplier selection problems may be found, among others, in papers [7, 8, 9].

The developed methods of supplier selection for producers of electrical and electronic devices refer to the presented issues. These differ in taking into consideration the requirements set for producers of components and subassemblies for these devices. The methods developed feature multicriteria and hierarchical (multilevel) approach to problem solution and use of linear mathematical models. These methods allow not only selection of suppliers but also designing schedules for deliveries for selected suppliers. The problems connected with scheduling have been discussed, among others, in the works [10, 11, 12], while hierarchical approach to task scheduling has been widely studied in [13, 14, 15].

Calculation experiments have been conducted for the developed methods, and the results used for comparison of these methods are given.

2. Concepts of methods

Some methods have also been developed for simultaneous support of many producers of electric and electronic equipment who are recipients of components. The components supplied are called products. There is a set of suppliers I who deliver products to recipients from the set J. The demand is known for individual recipients in specific periods of time for each product from the set K. The supply of products in the consecutive analysed periods is also given. Suppliers of the products for individual recipients should be selected so that demand is met, with the simultaneous consideration of many criteria. The next chapter describes all the criteria which are taken into account and the parameters defined for the mathematical description of the problem.

The developed methods are used to support designing supply networks and control product flow. They have been developed for supply chains of network nature. A sample structure of a part of such a chain is given on Figure 1.

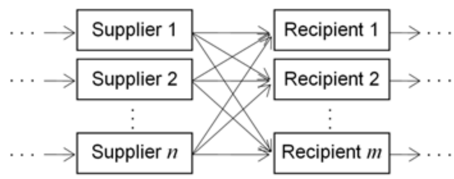

Figure 1. Example of fragment of supply network structure

For such configurations of supply chains, two two-level methods have been developed: M1, M2. Block diagrams of these methods are given on Figure 2. At the first level of each of these methods, preliminary, multi-criteria selection of suppliers is performed. Its purpose is to reduce a large number of parameters which are taken into account at the second level of the method. The multi-criteria AHP (Analytic

Hierarchy Process) method is used for this purpose, developed by Satty [16].

The suppliers who are ranked best in the initial selection are then taken into account at the second level of the method. For this level, a linear model of the mathematical programming problem has been developed, presented in Chapter 4. Handling costs for producers of electric and electronic equipment are then minimised. All decision variables formulated for the M1 method are in integral numbers. As a result, the final solution is optimum in terms of the adopted criterion.

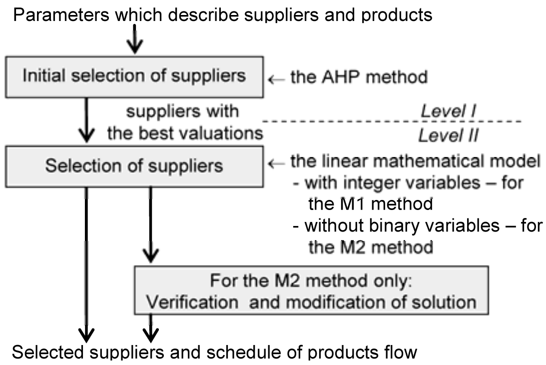

Figure 2. Block diagrams of the methods

To enable solving tasks of major scale within relatively short time, the M2 method has been developed. Unlike the M1 method, the second level of the M2 method is dedicated to solving a mathematical programming problem with bypassing the integral-number nature of decision variables. This concept requires a procedure to be applied which verifies and modifies the solution. This relaxation heuristics is described in Chapter 5. Both methods have been compared, and the results of calculation experiments are given in Chapter 6.

3. Data and selection of data

The initial selection of suppliers conducted at the first level of both methods with the AHP method is to reduce a large number of parameters and mathematical relationships which are taken into account in the mathematical model developed for the second level of the method. Some examples of applications of the AHP method in multi-criteria assessment may be found in, among others: [17] and [18].

The multi-criteria AHP method was adjusted to the requirements posed for suppliers who provide components for producers of electric and electronic equipment. It is reflected in defining criteria of supplier selection. The number of criteria is significant here. Insufficient number of criteria limits the possibility of analysing many aspects, whereas excess number of criteria contributes to the necessity of solving problems related to selection of weights.

With the above aspects included in the method of supplier selection, 8 main criteria given in Table 1 have been chosen.

The criteria given in Table 1 should be assigned weights. For this purpose, the rules have been taken into account which were developed by T. L. Satty for the AHP method [16]. The values of weights determined for the criteria taken into account in the examples used for testing the method are presented in Chapter 6.

Several suppliers who won the highest total assessment grades are taken into account in the final selection of suppliers. As a result, only parameters of the initially selected suppliers are taken into account at the second level in each of the methods. The list of indexes, parameters and variables defined to be used in the mathematical programming method are given in Table 2.

Table 1. Summary of main and detailed criteria

Symbol	Main criteria	Detailed criteria
C_1	Quality	compliance with standards, technological quality of machine parts, functioning of the quality control system
C_2	Time	timely deliveries, readiness to work following conditions of the client, speed in execution of orders
C_3	Price	stability of price, costs of transport, discount
C_4	Maintenance	location of storage facilities for spare parts, conditions for processing complaints and repairing parts
C_5	Reliability	regular deliveries, reliability of deliveries
C_6	Potential	production control, technical capacity
C_7	Financial standing	solvency of the supplier (long-term support)
C_8	Location	possibility of execution of urgent orders, possibility of close cooperation

Table 2. Summary of indices, parameters and variables

Indices:		
i	=	supplier; $i \in I$;
j	=	recipient; $j \in J$;
k	=	product; $k \in K$;
l	=	time interval (period); $l \in L$;
Parameters:		
a_{ijk}	=	minimum number of products k, sold by supplier i to recipient j, which grants rights to discount;
b_{ijk}	=	amount of the discount granted to recipient j by supplier i due to one-time sale of products k in the number of at least a_{ijk};
c_{ik}	=	price of product k, sold by supplier i (without discount);
c_{3ij}	=	cost of one-time use of a means of transport between supplier i and recipient j (without discount);
d_{ijl}	=	estimated minimum price of the transport service between supplier i and recipient j, executed within time l;
e_{jk}	=	penalty for each period of delay in delivery of product k to supplier j;
f_{jk}	=	cost of storing the prematurely provided product k with supplier j, incurred within the unit of time;
m_l	=	maximum number of suppliers supporting recipient j;
p_{jkl}	=	volume of demand in plant j for the products k during the period l;
s_{ikl}	=	number of products k available in period l from supplier i (supply);
A	=	the set of pairs (j, k), in which recipient j has demand for products k;
K	=	the set of pairs (i, k), in which supplier i produces products k;
P	=	the set of three elements (i, k, l), in which producer i has products k available for transport during period l;
R	=	the set of three elements (j, k, l), in which recipient j has demand for products k in period l;
U	=	the set of three elements (i, j, k), in which producer i, supplying products k to supplier j, applies discounts related to ordering the appropriate volume of these products k.
α	=	any integral number larger than the number of the considered periods l;
β	=	any integral number larger than the number of all units of the considered type products k;
Variables:		
q_{jkl}	=	number of missing products k with supplier j during period l;
w_{jkl}	=	number of products k in surplus with supplier j

		during period l;
x_{ijkl}	=	number of units of the products k transported during period l between supplier i and recipient j;
u_{ij}	=	1, if supplier i delivers products to recipient j, otherwise u_{ij} = 0;
y_{ijk}	=	1, if the number of products k ordered for one transport between supplier i and recipient j is at least a_{ijk}, otherwise y_{ijk} = 0;
z_{ijl}	=	1, if during period l transport is executed between supplier i and recipient j, otherwise z_{ijl} = 0.

4. Mathematical model

After the initial selection of suppliers, the problem formulated in the linear mathematical model is solved. For the M1 method, the relationships (1) to (11) must be taken into account at the same time [19]. Those given in (1) to (10) refer to the M2 method.

Here is the mathematical model built for the M1 and M2 methods:

Minimize:

$$(1)\quad \sum_{i\in I}\sum_{j\in J}\sum_{k\in K}\sum_{l\in L} c_{ik}x_{ijkl} - \sum_{i\in I}\sum_{j\in J}\sum_{k\in K} b_{ijk}y_{ijk} + \sum_{(i,j,l)\in T} d_{ijl}z_{ijl} + \sum_{(j,k)\in A}\sum_{l\in L}\left(e_{jk}q_{jkl} + f_{jk}g_{jkl}\right)$$

Subject to:

$$(2)\quad \sum_{i\in I}\sum_{l\in L:(i,j,l)\in T} x_{ijkl} \ge \sum_{l\in L:(j,k,l)\in R} p_{jkl};\ j\in J; k\in K$$

$$(3)\quad \sum_{j\in J:(i,j,l)\in T} x_{ijkl} \le \sum_{\tau\in L:\tau\le l\wedge(i,k,\tau)\in P} s_{ik\tau};\ i\in I; k\in K; l\in L$$

$$(4)\quad \sum_{\tau\in L:\tau\le l}\sum_{i\in I} x_{ijk\tau} + - \sum_{\tau\in l:\tau\le l\wedge(j,k,\tau)\in R} p_{jk\tau} \le g_{jkl};\ j\in J; k\in K; l\in L$$

$$(5)\quad \sum_{\tau\in L:\tau\le l\wedge(j,k,\tau)\in R} p_{jk\tau} + - \sum_{\tau\in l:\tau\le l}\sum_{i\in I} x_{ijk\tau} \le q_{jkl};\ j\in J; k\in K; l\in L$$

$$(6)\quad \sum_{k\in K} x_{ijkl} \le \alpha\cdot z_{ijl};\ i\in I; j\in J; l\in L$$

$$(7)\quad \sum_{l\in L:(j,k,l)\in R} x_{ijkl} \ge a_{ijk}y_{ijk};\ (i,j,k)\in U$$

$$(8)\quad x_{ijkl} \le \beta u_{ij};\ i\in I; j\in J; k\in K; l\in L$$

$$(9)\quad \sum_{i\in I} u_{ij} \le m_j;\ j\in J$$

$$(10)\quad g_{jkl}, q_{jkl}, x_{ijkl} \ge 0;\ \text{integer};\ i\in I; j\in J; k\in K; l\in L$$

Only for the M1 method:

$$(11)\quad u_{ij}, y_{ijk}, z_{ijl} \in \{0,1\};\ i\in I; j\in J; k\in K; l\in L$$

The minimized sum (1) includes costs of: purchasing products (including discounts), transporting, penalties for each contractual period in delay of deliveries of individual products and costs of storing the products which were supplied earlier. The costs of transport are given as estimation only. The location of the plants which produce components for electric and electronic equipment is important in selection of suppliers, as costs of transport depend on it. The adopted cost criterion helps to find such schedules of deliveries in which products are supplied in the periods as near the dates of order execution as possible (known from the p_{jkl} parameter, given in Table 2.

The limitation (2) ensures delivery of the required number of products (components) to each recipient–producer of electric or (and) electronic equipment. Availability of these products in specific periods of time from the given supplier is verified according to (3). The condition (4) is used to determine the number of individual products delivered early to producers of hardware, i.e. products with storage costs applied. Quantities of the products needed by the recipients are determined for individual periods of time and are known due to the constraint (5). This dependence affects the amounts of penalties incurred for delays in deliveries. Demand for use of means of transport in particular periods of time for travels between selected suppliers and recipients is known from the dependency (6). The condition (7) is used to verify the possibility of granting discounts for the given recipients on the basis of ordering the stated number of products. The list of suppliers of the products is determined on the basis of the relationship (8). The number of suppliers who support each of the recipients may be limited with the condition (9). Obviously enough, this limitation may be omitted. The model may be used for calculation experiments which consist in verifying the effect of the number of suppliers on deadlines for deliveries and the resulting costs. Increase in the number of suppliers often results in reduction of the amount of discounts for purchase of products and reduction in penalties for delays in deliveries, but causes increase in transport costs. The limitations (10) and (11) ensure the use of the appropriate types of variables.

The M1 method ends with solution of the problem described in the linear mathematical model with the formulae (1) to (11). With discrete optimization, the results of the tasks solved at the second level of the method are optimum. Known are not only suppliers for producers of equipment (the value of the variable u_{ij}, defined in Table 2), but also schedules for product deliveries (on the basis of the value of the variables: x_{ijkl}, z_{ijl}).

5. Relaxation heuristic

To enable solving problems of significant size within a relatively short time, relaxation heuristics has been developed. It is based on application of the linear mathematical model formulated in the relationships (1) to (10).

Here are the steps in the heuristic M2 method:

Step 1. Solution of a linear programming problem.

Solve the problem formulated in mathematical relationships (1) to (10) with the condition (12) met.

$$(12)\quad u_{ij}, y_{ijk}, z_{ijl} \ge 0;\ i\in I; j\in J; k\in K; l\in L$$

Assume the number of iterations $h := 1$. Define the heuristic initial solutions for the variables for which the binarity condition was rejected according to (13). Assume $h := h + 1$ and go to Step 2.

$$(13)\quad \tilde{u}^h_{ij} = u_{ij},\quad \tilde{y}^h_{ijk} = y_{ijk},\quad \tilde{z}^h_{ijl} = z_{ijl};\quad i\in I; j\in J; k\in K; l\in L$$

Step 2. Determining discrete solutions.

Make approximations according to (14). Go to Step 3.

$$(14)\quad \tilde{u}^h_{ij} = \mathrm{round}\left(\tilde{u}^{h-1}_{ij}\right),\quad \tilde{y}^h_{ijk} = round\left(\tilde{y}^{h-1}_{ijk}\right),\quad \tilde{z}^h_{ijl} = round\left(\tilde{z}^{h-1}_{ijl}\right);\quad i\in I; j\in J; k\in K; l\in L$$

Step 3. Preliminary determination of suppliers [20].

Check whether at least one supplier has been selected for each recipient j. If no supplier has been selected for the recipient j, select the supplier i for whom the value of the variable $\tilde{u}_{ij}^{h-1}$ is largest. If the value of this variable is identical for several suppliers, take into account the following lexicographical order: the supplier with the lowest index who meets the conditions (2) and (3); the supplier with the lowest index. Assume $h := h + 1$. Update the values of the variables which determine the selection of the suppliers and go to Step 4.

Step 4. Verification of the quantity of the ordered products.

a. Let I_j mean a set of suppliers selected for the recipient j. Assume $j := 0$ and $k := 0$, go to Step 4b.
b. Assume $k := k + 1$ and go to Step 4c.
c. Assume $j := j + 1$. If the relationship (15) is met (which is a modification of the inequality (2)), go to Step 4d; otherwise, add further suppliers according to the lexicographical order so that the condition (15) is maintained: the supplier with the highest supply during the demand period; the supplier who sells products at the lowest prices; the supplier with the lowest index. Go to Step 4d.

$$\sum_{i \in I_j} \sum_{l \in L:(i,j,l) \in T} x_{ijkl} \geq \sum_{l \in L:(j,k,l) \in R} p_{jkl}; \; j \in J; k \in K \tag{15}$$

d. If $k < K'$ (K' – the number of types of products), go back to Step 4b; otherwise check whether $j < J'$ (J' – the number of recipients). If this inequality is met, go to Step 4c, otherwise save the selected suppliers and go to Step 5.

Step 5. Verification of availability of the ordered products.

a. Assume $i := 0$ and $k := 0$ and go to Step 5b.
b. Assume $k := k + 1$ and go to Step 5c.
c. Assume $i := i + 1$. If the relationship (16) is met, go to Step 5d; otherwise add further suppliers (select the suppliers) so that the condition (16) is maintained, according to the lexicographical order: the supplier with the largest inventory during the demand period; the supplier who sells products at the lowest prices; the supplier with the lowest index.

$$\sum_{j \in J} x_{ijkl} \leq \sum_{\tau \in L, \tau \leq L} d_{ikl}; \; l \in L \tag{16}$$

d. If $k < K'$, go back to Step 5b; otherwise check the relationship: $i < I'$ (I' – the number of suppliers of components). If this inequality is maintained, go to Step 5c; otherwise assume $h := h + 1$, save the selected suppliers and go to Step 6.

Step 6. Building the schedule of deliveries.

Modify the set of data: remove the suppliers who have not been selected, along the parameters which describe them. In order to determine the schedule of product deliveries with the selected suppliers taken into account, solve the problem formulated in the mathematical relationships (1) to (11) with omission of the limitations: (8), (9), and including additional equations (17) and (18). Adding the relationships (17) and (18), which take into account the solution determined in the preceding steps of heuristics, helps vastly reduce the search space and solve the problem in a relatively short time. At the same time, fewer mathematical relationships are taken into account, with a smaller number of parameters and variables, when compared with the original problem. Complete the calculations.

$$x_{ijkl} = 0; \; i \in I; \; j \in J; \; k \in K, \; l \in L; \; \tilde{u}_{ij}^{h} = 0 \tag{17}$$

$$z_{ijl} = 0; \; i \in I; \; j \in J; \; l \in L; \; \tilde{u}_{ij}^{h} = 0 \tag{18}$$

6. Computational experiments

The methods developed have been verified in calculation experiments. The discrete optimisation package along with the AMPL language (A Mathematical Programming Language) has been used in them [21].

There were 10 suppliers in each one of the test examples. They have been assessment in terms of 8 criteria. In accordance with the procedure used for the AHP method, particular criteria have been compared with each other. The indications of criteria frequency have been used to determine weights for each one of the criteria. The indications of frequency of criteria advantages and their structural weights are given in Table 3.

Table 3. Indications of frequency of criteria advantages and their structural weights

Symbol	Main criteria	Quality	Time	Price	Maintenance	Reliability	Potential	Financial standing	Location	Frequency	Structural weights
C_1	Quality	C_1	C_2	C_3	C_4	*	C_1	C_7	C_1	3	0,088
C_2	Time	-	C_2	*	C_3	C_2	C_2	C_7	C_2	5	0,147
C_3	Price	-	-	C_3	C_3	C_3	C_3	C_7	C_3	8	0,235
C_4	Maintenance	-	-	-	C_4	C_5	C_4	C_7	C_4	4	0,118
C_5	Reliability	-	-	-	-	C_5	C_3	C_7	C_5	3	0,088
C_6	Potential	-	-	-	-	-	C_6	C_7	C_8	1	0,029
C_7	Financial standing	-	-	-	-	-	-	C_7	C_7	8	0,235
C_8	Location	-	-	-	-	-	-	-	C_8	2	0,059

The parameters of the four test groups in the problems are given in Table 4. At the second level of the methods, 3 or 4 suppliers were taken into account who won the highest total marks.

The conducted calculation experiments were aimed at comparing the M1 and M2 methods. For this purpose, three indicators have been used. The indicator defined in the relationship (19) is used to compare the resulting schedules of deliveries. To compare the incurred costs, determined according to (1), the indicator is used which is described in the relationship (20). The times of calculations have also been compared according to (21). For each of the test problem groups, 20 examples were solved. The average values of the obtained results are given in Table 4.

$$\gamma = \left(C_{\max}^{M2} - C_{\max}^{M1}\right) / C_{\max}^{M1}, \tag{19}$$

where: $C_{\max}^{M1}, C_{\max}^{M2}$ - the schedule lengths of transport tasks, using the methods: M1, M2.

$$\psi = \left(\kappa^{M2} - \kappa^{M1}\right) / \kappa^{M1}, \tag{20}$$

where: κ^{M1}, κ^{M2} – the costs calculated by (1), using by the methods: M1, M2.

$$\sigma = CPU^{M1} / CPU^{M2}, \tag{21}$$

where: CPU^{M1}, CPU^{M2} – the times of calculation with use the M1, M2 method.

Table 4. Parameters of groups of tasks and average values of results

Parameters of groups of tasks					Indexes		
Group	*I'*	*J'*	*K'*	*S'*	γ [%]	ψ [%]	σ [%]
1	3	3	6	800	7,3	8,2	15,2
2	3	3	8	1200	6,7	7,5	17,6
3	3	4	10	1600	6,4	7,1	20,4
4	4	4	10	2000	6,3	6,8	24,5

Numbers of: *I'* – suppliers, *J'* – recipients, *K'* – types of products, *S'* – units of the all products

The presented results of calculation experiments indicate extension of the schedules by about 6 to 7% (the γ index) in case of using the M2 heuristic method against the M1 method, based on application of discrete optimisation. The schedules of deliveries built based on the M2 method, longer than in case of the M1 method, caused several-per cent increase in costs of supply network operation, which is apparent from the average values of the index ψ. Along with the increase in size of the test problems, the average values of the γ, ψ indexes were dropping down. It is important to note that the scale of the test problems was not excessive. This was connected with possibilities of the packages of discrete optimization: a limited number of variables, time required for the calculations. The advantage from application of the heuristic M2 method comes in reducing the time of calculations several times when compared with the M1 method, which is proven with the σ index. For larger problems, solved with the M2 heuristics, more favourable values of the σ index are expected when compared with the M1 method.

7. Conclusion

The advantages of the developed methods include the multicriteria approach to the problem of supplier selection and the hierarchical approach to its solution. Simultaneous taking many criteria into consideration is conducive for finding the best solutions in the form of the schedules of product deliveries to producers of electric and electronic equipment. The multicriteria and, at the same time, hierarchical approach to the solution of the problem allows a very large number of parameters, variables and mathematical relationships formulated for the supplier selection task to be taken into consideration.

The methods have been built to support designing of supply networks. The requirements set for suppliers of components for electrical and electronic equipment are reflected in the selection of criteria and their weights, as well as in the formulated mathematical model. Modification of the methods, which consists in changing some criteria, may enable application of these methods for selection of producers of other goods.

The developed M2 heuristics is mostly recommended for solving problems of major size, which cannot be solved with discrete optimisation. To solve problems of relatively small size, the M1 method is recommended. At the second level of this method, a solution is determined which is optimum in view of the adopted cost criterion. The development of computer technology and software favour development of methods based on integer programming.

The developed mathematical model may be modified and expanded, thus being adjusted to the requirements of the recipients.

The presented methods are applicable mostly when the recipients are within one network. The interests of individual recipients (the links of this network) may differ from the interest of the total structure, though. The mathematical model built for the methods may be used in some simulations. In these experiments, recipients themselves assess advantages of their belonging to the network. However, the fact has to be taken into account that selection of suppliers includes a number of factors other than the cost criterion, for example social aspects or these which are stated in the introduction to this paper.

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