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OPTIMISATION OF OPERATOR-MACHINE ASSIGNMENT PROBLEM USING EXCEL SOLVER

Abstract. *Although the fourth industrial revolution has greatly accelerated the automation of production processes, the importance of human resources has not diminished, as evidenced by the fact that multinational companies are increasingly investing more and more effort in determining the optimal allocation of machines and operators. In this paper, the authors present an approach to the operator-machine assignment task through a suitable model. The mathematical model presented is suitable to support the design of an appropriate human resource management strategy and the implementation of operative human resource management tasks in production systems of different sizes.*
Keywords: *assignment; operator; optimization; cost-efficiency; reject rate.*

1. INTRODUCTION

The design of material flow systems is becoming increasingly important in both on- and off-site value chains. The main reason for this is that, in addition to technological processes, the logistics processes that serve them are becoming increasingly important. The aim of this research is to identify possible solutions in the area of assignment task design, an important area of material flow system design, and to propose a solution that goes beyond these. In order to achieve this goal, a systematic literature review has been carried out as a first step, resulting in an examination of the main relevant design methods discussed in the literature. Subsequently, we briefly review the structuring of design tasks in material flow systems in order to identify the areas where it is possible to formulate specific design tasks as assignment tasks.

In the main part of the paper, we demonstrate the potentials of Excel Solver for different operator-machine allocation problems by solving optimization problems of different complexity. The article discusses the mathematical models of two typical assignment tasks that allow to describe different types of operator-machine assignment problems. Then, the implementation of the discussed assignment problems is described.

By examining the models and methods compared in the research work, we investigate the significance of transforming certain constraints into an objective function component and the impact of added constraint sets on the objective function value.

The models and methods presented in this work are suitable for optimising the allocation of process equipment, manufacturing and assembly cells and the operators serving them, even in large enterprises, resulting in increased production process efficiency, improved product quality through reduced reject rates and increased economic efficiency.

2. LITERATURE REVIEW

All research activities should be preceded by a literature review, which aims to identify areas of research relevant to the research objectives by looking at the existing research in the literature. In this chapter, we present the results of a systematic literature review to identify research results in the field of transportation and assignment problems and to identify areas where new research directions could be identified. To this end, we have divided the literature review into three major parts. In the first part, we describe a descriptive analysis of the literature sources in the relevant publication databases. In the second part, we provide an overview of the content of the literature sources identified and selected on the basis of various criteria, while in the third part we formulate our findings that contribute to the precise limitation of the research objective.

As a first step in the systematic literature review, we had to define search criteria to identify literature sources that fit well with our research objectives related to the study of transportation and assignment tasks. For our review, we first used the Scopus database and searched using the keyword (TITLE ("assignment problem") OR TITLE-ABS-KEY ("transportation problem")).

The search based on the keyword (TITLE ("assignment problem") OR TITLE-ABS-KEY ("transportation problem")) resulted 8771 publications. The research of assignment problems has a history of more than 60 years, while interestingly the earliest publication in the Scopus database in the field of transportation problems dates back to 1899 [1]. The first publication on solving assignment problems appeared in 1957 and focused on methods for solving assignment problems in directed graphs [2].

The number of publications shows a continuous increase (with the exception of a few years), but the trend in the number of publications shows that the research area is still relevant today, which we see as a result of the need to solve complex logistics problems in complex supply systems that require the development of increasingly complex solution methods.

An examination of the sources revealed that the majority of the articles were published in journals covering the fields of operations research, discrete applied mathematics and computer science. Based on the title and discipline of the sources that published a large number of articles, it can be concluded that heuristic optimization methods and artificial intelligence methods are playing an important role in solving assignment and transportation problems in complex supply chain planning. We found an interesting result when we examined the distribution of the number of published scientific results among researchers. Surprisingly, we were able to identify several researchers who had published more than 30 scientific results in Scopus database papers. This number indicates to us that several scientific workshops have developed over the decades that have made significant achievements in the field of research on transportation and assignment tasks.

We found similar results when analysing the affiliation of authors. Research groups with a large number of publications can be found in many countries around the world, in Europe, in America and in Asia. The same result is supported by the distribution of scientific papers by country, with the countries with the largest number of articles being China, India, France, Canada, Germany, Italy, Japan, Italy, Turkey, United Kingdom and the United States of America.

Focusing on the research topics, it can be observed that transportation and assignment tasks cover a wide range of different disciplines, with the following being of particular importance: computer science (4140 articles), engineering (3431 articles), mathematics (3315 articles), decision theory (1682 articles), social sciences (772 articles), business and management (765 articles), environmental science (278 articles).

This classification shows that our chosen research area fits well with engineering and applies knowledge from both computer science and mathematics. The explanation for this is that, since the transportation and assignment problems mainly seek solutions to problems that arise in the design of logistics processes in a large enterprise environment, the transport and assignment tasks are also mainly (but not exclusively) in the field of logistics. The importance of the information sciences lies in the fact that the design and management of complex supply chains requires the application of information and telecommunication technologies. The importance of the field of engineering implies that the problems involved in solving transportation and assignment tasks can generally be conceptualized as complex engineering systems. The large number of mathematical and decision making articles supports the fact that transportation and assignment problems require increasingly advanced solution methods, so that the use of newer and newer analytical and heuristic methods is inevitable. And the importance of business sciences draws attention to the important fact that cost-effectiveness is of great importance in the design of logistics systems, while environmental considerations are also inevitable. The categorization of the articles by keywords confirms the same facts from the point of view of the keywords used.

Following the statistical analysis, we examined a narrowed set of literature on assignment problems, analyzing the content of journal articles that are no older than 5 years and have the most independent citations. For the purpose of this analysis, we have chosen to analyze the content of articles focusing only on assignment problems. Articles focusing on assignment problems cover the following typical application areas: production logistics, supply chain planning, transportation management, warehousing logistics, warfare, education. The importance of these areas is demonstrated by the results of the following main research areas: modelling of real time ride sharing by linear assignment [3], traffic assignment problem [4], storage location assignment problems [5], assignment problems in socio-economic systems [6], assignment problems in optical networks [7], rapid drone assignment problems [8], weapon-target assignment [9], assignment of maintenance workers to maintenance tasks [10], assignment in education [11], restricted assignment problems [12], e-scooter assignment problems [13], period stochastic assignment problem for social engagement and opportunistic IoT [14], traffic assignment problems [15], assignment of nurse and patient [16], tail assignment problem [17], knapsack assignment problem [18].

Although an analytical solution of the assignment problem is possible, the constraints increase the complexity of the optimization problem to such an extent that the following heuristic and metaheuristic algorithms can be used: Whale algorithm and Tabu search [19], deep neural networks [20], Pareto-Ant Colony optimization [21], Birnbaum-heuristics [22], Discrete Bat heuristics [23].

In summary, research on assignment tasks has a history going back several decades. There are a number of applications that are not only of logistical relevance, but also concern many areas of production and civil services. A wide range of mathematical methods is available for solving transportation and assignment problems. These can be analytical methods for basic models of assignment problems, while for a large number of constraints the search space of the optimization problem requires the use of heuristic and metaheuristic algorithms. Based on the above conclusions drawn from the reviewed literature, we intend to investigate in our research to what extent the solution of transportation and assignment problems can be supported by Solver.

3. ASSIGNMENT PROBLEMS IN MATERIAL HANDLING DESIGN

The design problems of material flow systems can be traced back to a number of operational research problems. This chapter briefly describes examples of potential design problems that can be traced back to assignment problems [24, 25]. Layout planning, facility location: assignment of empty sites and objects to be installed, packaging, planning of unit loading: selection of optimal unit loading and packaging device, route planning: assignment of vehicles to routes, supply tasks to routes and assign collection and distribution tasks to routes and vehicles, design of queuing systems: assigning service tasks to resources, reliability of material flow systems: assigning tasks to resources and assigning resources to subsystems in order to design an optimal system structure to increase reliability.

4. OPERATOR MACHINE ASSIGNMENT WITH TRAINING OPTIONS

In the model, we consider as given the cost of assigning human resources (operators) to each technological resource (machine), the predicted reject rate of each operator on a given machine, the value of the planned quantities to be produced per shift on each machine, the cost of training of operators and the performance improvement as a result of training, which is reflected in the improvement of the reject rate:

- k_{ij}: assignment cost of operator *i* to machine *j*,
- s_{ij}: reject rate of operator *i* assigned to machine *j*,
- e_j: value of products to be produced on machine *j* within a shift,
- w: training cost of an operator, which can lead to a reject rate decrease of β.

The decision variable of the optimization problem is the matrices describing the assignment of human resources and technological resources and the training of human resources:

- x_{ij}: assignment of operator *i* to machine *j*:

$$\forall i,j: x_{ij} \in (0,1) \tag{1}$$

- x_i^*: training of operator *i*:

$$\forall i: x_i^* \in (0,1) \tag{2}$$

The objective function of the optimization task is to minimize the total cost:

$$C_6 = \sum_{i=1}^{m} \sum_{j=1}^{n} x_{ij} \cdot k_{ij} + \sum_{i=1}^{m} \sum_{j=1}^{n} x_{ij} \cdot \frac{s_{ij}}{1+x_i^* \cdot \beta} \cdot e_j + \sum_{i=1}^{m} w \cdot x_i^* \rightarrow min. \tag{3}$$

We can define two different constraints:

- each operator can be assigned to one machine:

$$\forall i: \sum_{j=1}^{n} x_{ij} = 1 \tag{4}$$

- each machine can be assigned to one operator:

$$\forall j: \sum_{i=1}^{m} x_{ij} = 1 \tag{5}$$

The input parameters of the scenario are the cost shown in Figure 1, the reject rate shown in Figure 2, the total value of products to be produced per shift per machine shown in Figure 3 and the training cost, which in this case study is 10 EURO/person.

Technological resources

Human resources: Cost	1	2	3	4	5	6	7	8	9	10	11	12
1	86	76	37	47	42	18	32	82	20	85	20	62
2	35	66	47	52	52	24	40	69	54	42	81	65
3	56	52	67	38	60	74	79	76	85	48	55	66
4	24	69	85	75	25	31	66	61	64	82	14	16
5	29	29	23	31	64	86	27	76	24	56	22	49
6	27	39	41	56	54	58	47	79	54	49	41	19
7	28	65	62	52	29	35	82	67	85	68	35	66
8	77	58	50	82	21	46	81	62	17	10	59	42
9	72	22	39	29	29	86	77	63	51	80	26	21
10	51	56	21	83	67	25	37	43	18	44	42	65
11	45	76	18	47	49	57	74	35	21	47	81	66
12	24	87	44	62	39	80	88	40	64	79	33	42

Figure 1 – The assignment cost of operators and machines

Technological resources

Human resources: Reject rate	1	2	3	4	5	6	7	8	9	10	11	12
1	2	5	1.1	1.2	0.8	4.3	1.3	0.3	3.6	1.3	4.4	2.7
2	0.4	2.7	1.6	4.3	3.9	0.3	3.7	0.6	1	3	0.2	4.8
3	1.9	3.9	2.7	0.8	3.3	0.5	3.1	3.4	0.9	4.4	3.3	0.1
4	1.9	4.9	3.2	1.3	1.1	4.9	4.8	0.1	3.7	2.5	0.3	3.5
5	1.4	3.5	3.7	1.6	2.9	4.6	2.3	1.1	2.3	1.3	0.8	4.1
6	0.8	1	0.1	0.9	3.2	3.5	2	1	2.6	1.9	1.2	3.2
7	3.5	3.8	1.8	3.6	4.4	1.6	0.6	0.6	0.8	4.1	2.6	2
8	4.1	3.8	1.2	5	1.3	4.6	4	4.9	0.2	0.6	2.8	2.6
9	3	3.5	1.9	3.5	2.7	2.4	0.1	3.9	4.5	1.8	3.1	1.2
10	0.3	3.1	5	2.4	0.3	5	1.9	3	1.2	0.5	1.2	1.7
11	5	2.9	1.7	0.2	1.3	4.8	0.2	0.1	1.3	0.3	4.3	1
12	2.1	2.1	2.5	0.6	3.6	3.2	1.8	3.1	4.1	3.9	4.5	1.8

Figure 2 – The reject rate of operators assigned to different machines

Technological resources

	1	2	3	4	5	6	7	8	9	10	11	12
Value to be produced	3500	5600	1500	2650	4570	9510	1500	980	12000	5400	3200	6540

Figure 3 – Value to be produced per shift per machine

The solution is illustrated in Figure 4 and Figure 5. The integrated assignment matrix shown in Figure 4 contains both the assignment of human resources and technological resources and the assignment of human resources to training.

Technological resources

Human resources	1	2	3	4	5	6	7	8	9	10	11	12	Training
1	0	0	0	0	1	0	0	0	0	0	0	0	1
2	0	0	0	0	0	1	0	0	0	0	0	0	0
3	0	0	0	1	0	0	0	0	0	0	0	0	1
4	0	0	0	0	0	0	0	0	0	0	1	0	0
5	0	0	0	0	0	0	1	0	0	0	0	0	1
6	0	1	0	0	0	0	0	0	0	0	0	0	1
7	0	0	0	0	0	0	0	1	0	0	0	0	0
8	0	0	0	0	0	0	0	0	1	0	0	0	1
9	0	0	0	0	0	0	0	0	0	0	0	1	1
10	0	0	0	0	0	0	0	0	0	1	0	0	1
11	0	0	1	0	0	0	0	0	0	0	0	0	1
12	1	0	0	0	0	0	0	0	0	0	0	0	1

Figure 4 – The integrated assignment matrix

The integrated assignment matrix in Figure 4 can be used to calculate the modified value of the reject rates shown in Figure 2, which is summarized in Figure 5. The cells in blue show the reduced reject rates.

Technological resources

Human resources	1	2	3	4	5	6	7	8	9	10	11	12
1	1	2.5	0.55	0.6	0.4	2.15	0.65	0.15	1.8	0.65	2.2	1.35
2	0.4	2.7	1.6	4.3	3.9	0.3	3.7	0.6	1	3	0.2	4.8
3	0.95	1.95	1.35	0.4	1.65	0.25	1.55	1.7	0.45	2.2	1.65	0.05
4	1.9	4.9	3.2	1.3	1.1	4.9	4.8	0.1	3.7	2.5	0.3	3.5
5	0.7	1.75	1.85	0.8	1.45	2.3	1.15	0.55	1.15	0.65	0.4	2.05
6	0.4	0.5	0.05	0.45	1.6	1.75	1	0.5	1.3	0.95	0.6	1.6
7	3.5	3.8	1.8	3.6	4.4	1.6	0.6	0.6	0.8	4.1	2.6	2
8	2.05	1.9	0.6	2.5	0.65	2.3	2	2.45	0.1	0.3	1.4	1.3
9	1.5	1.75	0.95	1.75	1.35	1.2	0.05	1.95	2.25	0.9	1.55	0.6
10	0.15	1.55	2.5	1.2	0.15	2.5	0.95	1.5	0.6	0.25	0.6	0.85
11	2.5	1.45	0.85	0.1	0.65	2.4	0.1	0.05	0.65	0.15	2.15	0.5
12	1.05	1.05	1.25	0.3	1.8	1.6	0.9	1.55	2.05	1.95	2.25	0.9

Figure 5 – The modified reject rates

The optimization resulted the following costs: cost of assignment of human resources to technological resources 375 EURO, training cost 90 EURO, reject value 232.4 EURO and total cost 697.4 EURO. The Excel Solver implementation of the solution and its relation to the mathematical model is illustrated in Figure 6.

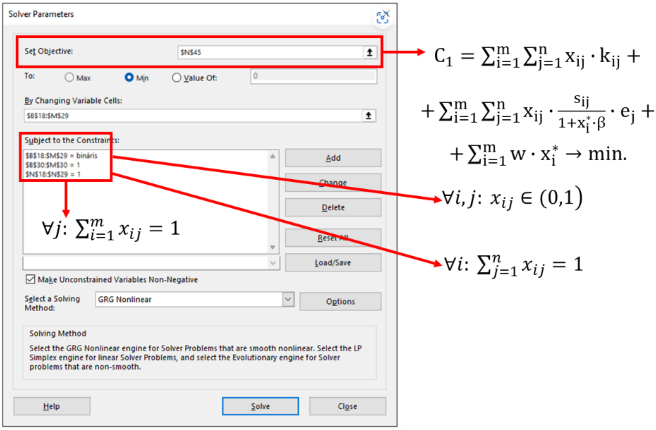

Figure 6 – The Excel Solver implementation of the solution and its relation to the mathematical model

The impact of training cost on the cost structure of the optimal solution is shown in Figure 7.

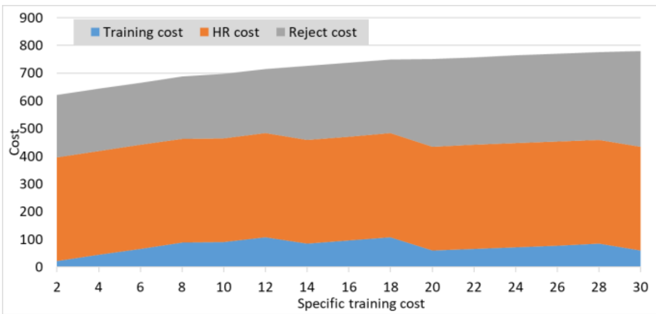

Figure 7 – Impact of specific training cost on the cost structure of optimal solution

5. DISCUSSION AND CONCLUSIONS

An important part of the design and operation of material flow systems in manufacturing processes is the solution of transportation and assignment tasks. The goal of this research work was to develop a mathematical model for the optimal assignment of operators (human resources) and machines (technological resources) in complex manufacturing environment. To achieve this goal, the main tasks in the design of material flow systems (especially in in-plant supply) have been investigated and the typical assignment tasks they represent have been presented. Several methods are available for solving these assignment problems (Northwest corner method, minimum cost method, Vogel method), but when the objective functions and constraints subject to optimization are complex, new solutions are needed to solve the problem under consideration. In this research work, we investigated whether Excel Solver is suitable for solving complex assignment tasks. Having established that Excel Solver is suitable for solving complex assignment tasks, we have developed a mathematical model that is suitable for assigning operators to machines, while also analyzing the potential performance improvements that can be achieved through worker training. The most important consequences of our analysis can be summarized as follows:

- The more constraints are taken into consideration, the more the optimal solution decreased. This is a trivial fact follows from the nature of optimization problems. It is important to note that this statement is only trivial and true if we add constraints to an existing constraint set. Replacing a smaller set of constraints with a larger set of constraints does not necessarily imply a decreasing objective function value in the case of maximization.
- If a constraint is integrated into the objective function, the solution can be significantly improved. For example, as long as only a constraint on the reject rate that can be produced on technological resources is formulated, a worse solution is obtained than when this reject value is integrated into the cost function as objective function.
- Training of operators can improve their performance, which can lead to a decreased reject rate, but since training has also significant cost, training of human resources may not be appropriate. This conclusion should be treated with caution, as the time horizon over which the return of training is interpreted is very important. In the case of short-term employment, the cost of training is less profitable than in the case of long-term employment.

The practical impact of the research work presented above can be summarized as follows:

- the presented model and solution method can be used to assign human resources (operators) to production resources (production tasks) in a real production environment,
- as a result of the optimization discussed, the utilization of human resources can be increased, the quality of products can be improved by reducing the reject rate, and a more cost-efficient production system can be operated.

Future research plans include further extension of the models and the investigation of methods for solving large-scale complex problems. An important further development could be the inclusion of uncertainty factors.

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ОПТИМІЗАЦІЯ ЗАДАЧІ ПРИЗНАЧЕННЯ ОПЕРАТОР-МАШИНА ЗА ДОПОМОГОЮ EXCEL SOLVER

Анотація. *Незважаючи на те, що четверта промислова революція значно прискорила автоматизацію виробничих процесів, важливість людських ресурсів не зменшилася, про що свідчить той факт, що багатонаціональні компанії все частіше вкладають все більше зусиль у визначення оптимального розподілу машин і операторів. Розробка систем матеріальних потоків стає все більш важливою в ланцюжках створення вартості як на місці, так і за його межами. Основна причина цього полягає в тому, що, крім технологічних процесів, все більшого значення набувають логістичні процеси, які їх обслуговують. Важливою частиною проектування та експлуатації систем матеріальних потоків у виробничих процесах є вирішення завдань транспортування та призначення. Метою цієї дослідницької роботи була розробка математичної моделі для оптимального розподілу операторів (людських ресурсів) і машин (технологічних ресурсів) у складному виробничому середовищі. Для досягнення цієї мети були досліджені основні завдання при проектуванні систем матеріальних потоків (особливо при внутрішньозаводському постачанні) та представлені типові завдання призначення, які вони представляють. Існує кілька методів для вирішення цих проблем призначення (метод північно-західного кута, метод мінімальних витрат, метод Фогеля), але коли цільові функції та обмеження, що підлягають оптимізації, є складними, для вирішення проблеми, що розглядається, необхідні нові рішення. У цій дослідницькій роботі автори з'ясували, чи підходить Excel Solver для розв'язування складних завдань. Встановивши, що Excel Solver підходить для вирішення складних завдань призначення, автори розробили математичну модель, яка підходить для призначення операторів машинам, а також аналізуючи потенційні покращення продуктивності, яких можна досягти шляхом навчання працівників. Найважливіші наслідки аналізу авторів можна підсумувати таким чином: чим більше обмежень береться до уваги, тим більше зменшується оптимальне рішення. Якщо сформульовано лише обмеження на відсоток браку, який може бути створений за допомогою технологічних ресурсів, буде отримано гірше рішення, ніж коли це значення браку інтегровано у функцію витрат як цільову функцію. Навчання операторів може підвищити їх продуктивність, що може призвести до зниження відсотка відмов, але оскільки навчання також вимагає значних витрат, навчання людських ресурсів може бути недоречним. Представлена модель і метод рішення можуть бути використані для призначення людських ресурсів (операторів) виробничим ресурсам (виробничим завданням) у реальному виробничому середовищі. В результаті обговорюваної оптимізації можна підвищити використання людських ресурсів, покращити якість продукції за рахунок зменшення відсотка браку та запровадити більш економічно ефективну систему виробництва.*

Ключові слова: *призначення; оператор; оптимізація; економічність; брак.*