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Efficient Modification of the CRAFT Algorithm for Layout Optimisation

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Abstract: Every combination of product mix and production volume requires a suitable layout of workplaces (functional units). An optimised layout is of utmost importance to achieve global competitiveness of companies and to build an efficient, sustainable production. We plan the layout mainly with heuristic methods; constructive, improvement and combined methods are available. In this paper, a modification of the established improvement algorithm CRAFT (exchange method) is presented, which provides much better and more accurate results at a slightly higher computational cost. The most important change is the immediate precise determination of the centroids of the areas of workplaces (or departments) that are exchanged. The distance between any two workplaces is represented by the orthogonal distance between the centroids. In the example given, which is based on a pairwise exchange, the difference is 22 % in favour of the modified algorithm.

Keywords: algorithm modification; CRAFT method; layout optimisation; pair-wise exchanges; production layout

1 INTRODUCTION

One of the prerequisites for companies to achieve global competitiveness is the optimal spatial arrangement (layout) of workplaces. The correct and optimal arrangement of workplaces in the production system primarily affects the flow of work items, as well as the flow of information and energy. We want to reduce the costs of internal logistics, i.e. the variable costs of transporting materials between workplaces, as much as possible through a clever arrangement of workplaces. The method of layout planning is largely determined by the type of production; we distinguish between flow line (continuous), intermittent (batch, job shop) and project (individual) production. The flow of the production process and the quantities of material moving through the process are fundamental, so how we arrange the different workplaces in the workshops (departments) is extremely important. We can consider quantitative criteria for the layout, determined by measurable quantities (e.g. transport costs), or qualitative criteria if we cannot determine a measurable material flow, customer flow, etc. between the workplaces and judge which workplaces should be close to or far away from others.

The problem of designing the layout of workplaces is generally the placement of *n* workplaces (or technological systems) at *n* or more possible locations, whereby the target function must be fulfilled or the optimum solution found. This theoretically results in *n*! layout variants, but due to the large size it is not possible to calculate them all [1].

In the following, we restrict ourselves to intermittent production, which comprises a variety of products in moderate quantities. The methods of layout planning are divided into construction methods (opening; we design the initial layout), improvement methods (we try to improve the initial layout) and combined methods (using the two previously mentioned methods). The available analytical (exact) layout planning methods are useful for a layout of max. 8 jobs and are useless for a larger number [2]. In practise, mainly heuristic methods are used due to the complexity of the problem. These methods do not provide optimal, but only sub-optimal layouts that are satisfactory for practical use.

The goals of an optimised workplace layout are:

- shorter transport routes,
- realisation of production in the required quantity, quality and on the desired deadlines,
- shorter throughput times for work orders,
- improved material flow,
- small stocks of unfinished products,
- more safety in the workplace,
- better efficiency of the production system,
- better control of the workplace,
- better communication between workers,
- better utilisation of space,
- better production flexibility,
- lower production costs,
- elimination of bottlenecks, etc.

The criterion for evaluating the placement of workplaces is the variable material transport costs (C_{tr}) between the workplaces, which are determined by Eq. (1) [3]:

$$C_{\mathrm{tr}} = \sum_{i=1}^{n} \sum_{j=1}^{n} C_{ij} D_{ij} F_{ij}, \tag{1}$$

where: n – number of workplaces in the material flow system, C_{ij} – the cost per unit distance for the transport between workplaces i and j, D_{ij} – the distance between the workplaces i and j, F_{ij} – the material flow between the workplaces i and j.

2 DESIGNING OPTIMAL LAYOUT

The initial layout of workplaces can be determined in different ways:

- using one of the construction methods (e.g. Schmigalla triangle method, ALDEP, CORELAP),
- on the basis of the real, existing layout (when reconstructing systems),
- randomly generated.

The optimal layout is determined by improving the initial solution until a satisfactory, sub-optimal layout of the workplaces is achieved. The use of computer programmes has facilitated and accelerated the search for optimal solutions, but a simple, perfect method has not yet been found. Layout improvement programmes carry out workplace relocations in order to reduce transport costs. The best-known programme is CRAFT (Computerised Relative Allocation of Facilities Technique) [4]. This is a classic method in which all possible pairs of workplaces or all triples are exchanged. The process ends when no exchanges bring additional gains, taking into account the target criterion (iterative sub-optimisation).

More recent publications also confirm the relevance of the problem of layout optimisation. Evolutionary optimisation methods are becoming increasingly important. Here are some brief descriptions.

Choi et al. [5] conducted a production simulation in the design phase to optimise the factory layout and used reinforcement learning to derive the optimal factory layout. The reinforcement learning process for optimising the individual components of the layout was implemented in several layers. Lind et al. [6] demonstrated an innovative approach to optimise the production layout that simultaneously considers worker welfare and system performance by using the Non-dominated Sorting Genetic Algorithm II and particle swarm optimisation. Shen et al. used spatial layout optimisation for a different goal – to improve evacuation efficiency in a building [7]. Zhao and Duan [8] described the application of deep reinforcement learning to solve the dual-objective optimisation problem for the layout of workshop facilities. They succeeded in reducing the computational effort. Rodriguez et al. adapted the Systematic Layout Planning methodology with an Industry 4.0 approach [9]. Gue et al. focused on optimising the layout of a workshop for discrete manufacturing based on a digital twin [10].

The CRAFT algorithm also frequently appears in publications that emphasise the practical application as well as the advantages and disadvantages of this method.

Sembiring et al. used the CRAFT algorithm to increase the company's productivity by determining the right plant layout to minimise material handling costs [11]. Prasad et al. used the CRAFT algorithm to design the layout of a production plant within a given area [12]. Amariei et al. present the design stages of a lower-rank production system using heuristic design methods, which are subsequently improved using the CRAFT algorithm [13]. Sadrzadeh presented a genetic algorithm to solve the plant layout problem and proved its efficiency in comparison with another genetic algorithm, the CRAFT algorithm and the entropy-based algorithm [14].

3 CRAFT ALGORITHM

CRAFT, the first computer-aided layout routine, appeared in 1963 [4]. Today, CRAFT is the most frequently used and best described routine for computer-aided layout planning. CRAFT is an improvement algorithm. The inputs to CRAFT include initial layout, flow data, cost per unit distance, total number of departments (workplaces), fixed departments (with locations), area of departments [15]. Fixed departments are usually fixed areas such as stairs, lifts, rest rooms, etc. In the final layout, the transport paths are also fixed areas. The steps of the CRAFT algorithm are:

Step 1. Inputs (as above).

Step 2. Calculate the centroids of the departments in the current layout.

Step 3. Form a distance matrix using the centroids.

Step 4. Calculate the total handling cost of the current layout using the flow, distance and cost data.

Step 5. Find all possible pairwise interchanges of departments based on common border or equal area criteria. Exchange the corresponding centroids for each possibility and calculate the approximate cost.

Step 6. Find the department pair with the lowest handling cost among all possible exchange pairs.

Step 7. Are the costs from the previous step less than the total cost of the present layout? If yes, go to Step 8, if not, go to Step 11.

Step 8. Interchange the selected pair of departments. Label this as the new layout. Calculate the centroids, the distance matrix and the total cost.

Step 9. Is the cost of the new layout less than the cost of the present layout? If yes, go to Step 10, if not, go to Step 11.

Step 10. The new layout is now considered to be the present layout, and its data on centroids, layout matrix and total cost are retained. Go to Step 5.

Step 11. Print the present layout as the final layout. Stop.

Candidates for exchange are characterised by at least one of the following properties: both workplace areas are the same size (but not necessarily the same shape) or the workplace areas have a common border. The exchange is carried out in such a way that the new workplace areas are as far away as possible from the old locations.

3.1 Numerical Example (Presented in [15])

The application of the CRAFT algorithm is shown in an example using the data:

- Total number of departments (n): 5
- Total number of interchangeable departments: 5
- Initial layout is shown in Fig. 1.

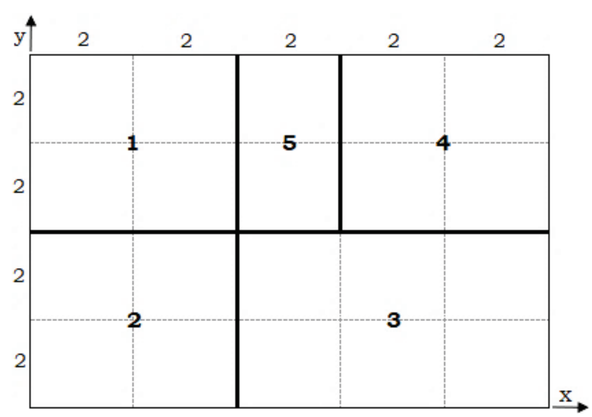

Figure 1 Initial layout for the numerical example

Area of departments 1 to 5: 16, 16, 24, 16, 8 (sq. units).

Cost data per unit distance from department i to department j:

$C_{ij} = 1$ ($i = 1, \dots, 5$; $j = 1, \dots, 5$ and $i \neq j$),

$C_{ij} = 0$ (when $i = j$).

The flow matrix [$\boldsymbol{F}_{ij}$] represents the number of trips in a given period from department i to department j:

From \ To	1	2	3	4	5
1	-	5	2	4	0
2	0	-	2	5	0
3	2	0	-	0	5
4	3	0	1	-	0
5	0	0	2	0	-

Centroids of all the departments in the initial layout:

$(X_1, Y_1) = (2, 6)$, $(X_2, Y_2) = (2, 2)$, $(X_3, Y_3) = (7, 2)$,
$(X_4, Y_4) = (8, 6)$, $(X_5, Y_5) = (5, 6)$.

The distance between any two departments is represented by orthogonal distance between the centroids:

$$D_{ij} = \left|X_i - X_j\right| + \left|Y_i - Y_j\right|. \tag{2}$$

The distance matrix [$\boldsymbol{D}_{ij}$]:

From \ To	1	2	3	4	5
1	-	4	9	6	3
2	4	-	5	10	7
3	9	5	-	5	6
4	6	10	5	-	3
5	3	7	6	3	-

Total transport cost matrix [$\boldsymbol{TC}_{ij}$]:

From \ To	1	2	3	4	5
1	-	20	18	24	0
2	0	-	10	50	0
3	18	0	-	0	30
4	18	0	5	-	0
5	0	0	12	0	-

Total (present) transport cost (C_{tr}) = 205.

Pairwise interchanges are considered. For the present problem, eight interchanges are possible at this stage: 1-2, 1-5, 2-3, 3-4, 3-5, 4-5 (on a common border); 1-4, 2-4 (on equal area).

Interchange between 1 and 2:

New centroids:

$(X_1, Y_1) = (2, 2)$, $(X_2, Y_2) = (2, 6)$, $(X_3, Y_3) = (7, 2)$,
$(X_4, Y_4) = (8, 6)$, $(X_5, Y_5) = (5, 6)$.

The distance matrix [$\boldsymbol{d}_{ij}$]:

From \ To	1	2	3	4	5
1	-	4	5	10	7
2	4	-	9	6	3
3	5	9	-	5	6
4	10	6	5	-	3
5	7	3	6	3	-

Total transport cost (C_{tr}) = 205.

We continue in the same way (here without the data on the centroids and the distance matrices):

Interchange between 1 and 4: C_{tr} = 193
Interchange between 1 and 5: C_{tr} = 208
Interchange between 2 and 3: C_{tr} = 197
Interchange between 2 and 4: C_{tr} = 201
Interchange between 3 and 4: C_{tr} = 178
Interchange between 3 and 5: C_{tr} = 183
Interchange between 4 and 5: C_{tr} = **163**

The interchange between 4 and 5 results in a minimum (approximate) cost of 163, which is less than the present layout cost of 205. The new layout after the actual interchange between 4 and 5 is shown in Fig. 2. The centroids and the distance matrix are updated. The centroids are:

$(X_1, Y_1) = (2, 6)$, $(X_2, Y_2) = (2, 2)$, $(X_3, Y_3) = (7, 2)$,
$(X_4, Y_4) = (6, 6)$, $(X_5, Y_5) = (9, 6)$.

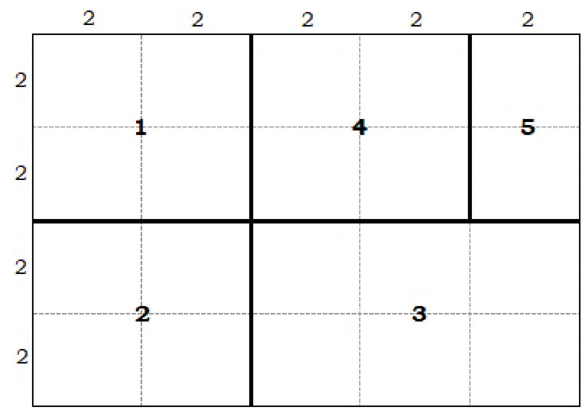

Figure 2 Layout after the 4-5 interchange

Total transport cost (C_{tr}) is 181. This is less than the present layout cost of 205. The new layout replaces the present layout, and we continue with the second iteration.

Six interchanges are possible: 1-2, 1-4, 2-3, 3-4, 3-5 (on a common border) and 2-4 (on equal area). The approximate total cost results for the same sequence of interchanges are: 181, 169, 209, 166, 183 and 181. 166 is the minimum C_{tr} (3-4). This is less than 181. The new layout is shown in Fig. 3.

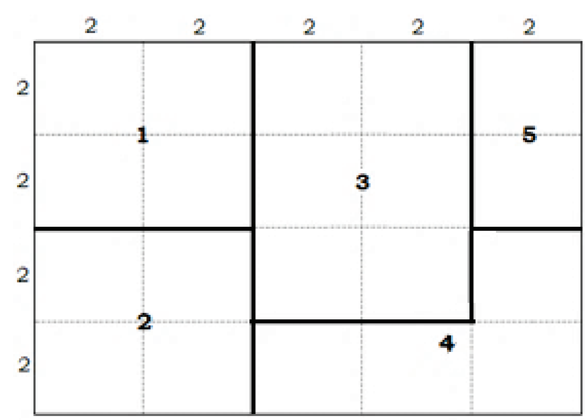

Figure 3 Layout after the approximate calculation in the 2nd iteration

New centroids for exact calculation are:

$(X_1, Y_1) = (2, 6)$, $(X_2, Y_2) = (2, 2)$, $(X_3, Y_3) = (6, 5)$,
$(X_4, Y_4) = (7.5, 1.5)$, $(X_5, Y_5) = (9, 6)$.

New distance matrix [d_{ij}]:

From \ To	1	2	3	4	5
1	-	4	5	10	7
2	4	-	7	6	11
3	5	7	-	5	4
4	10	6	5	-	6
5	7	11	4	6	-

Total transport cost (C_{tr}) is 187. This is more than the present layout cost, namely 181. The present layout is the final layout (C_{tr} = 181, which corresponds to a reduction of 12 % compared to the initial 205), see Fig. 4.

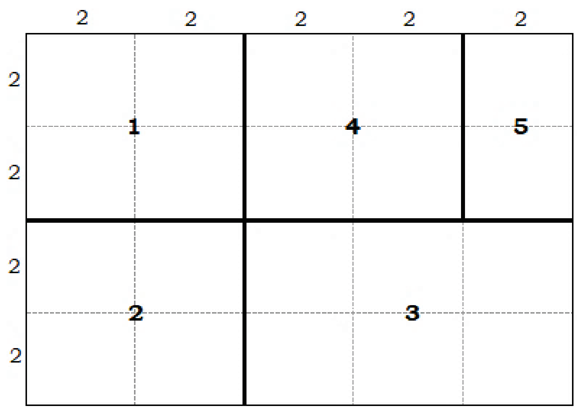

Figure 4 Final layout after the optimisation with the CRAFT algorithm

4 MODIFICATION OF THE ALGORITHM

The calculation of the approximate costs in Step 5 can lead to the optimal solution being lost. When exchanging the locations of departments, differences in distance occur due to different area sizes, so that with the CRAFT method it is always necessary to repeat the calculation with exact values. In our modification of the algorithm, however, we perform an exact calculation on-the-fly so that there are no deviations, and no additional calculation is required. The modifications can be seen in steps 5, 7, 8, 9 and 10:

Step 5. Find all possible pairwise interchanges of departments based on the criterion of common border or equal area. Calculate the exact new centroids and costs for each possibility.

Step 7. Are the costs from the previous step less than the total costs of the present layout? If yes, go to Step 8, if not, go to Step 9.

Step 8. Interchange the selected pair of departments. Label this as the present layout. Go to Step 5.

Step 9. Print the present layout as the final layout. Stop.

Step 10 is cancelled. Our algorithm requires about 10 times more computational effort but leads to a better solution.

4.1 Numerical Example (the Same Data as in Section 3.1)

Given initial layout is optimised with the application of the modified CRAFT algorithm to show its usefulness. For the purpose of cost calculation, an interchange between two departments would mean that their new centroids are calculated. For each interchange, the associated distance matrix is calculated. Then, the exact total transport cost is calculated.

The first iteration gives the same exchange decision as the original CRAFT algorithm (see Tab. 1). But the results for other iterations differ significantly.

Table 1 Exchange pairs and exact total transport costs (iteration 1)

Pair	1-2	1-4	1-5	2-3	2-4	3-4	3-5	4-5
C_{tr}	205	193	231	193	201	182	185	**181**

Layout after the iteration 1 (as in section 3.1), C_{tr} = 181, is shown in Fig. 5.

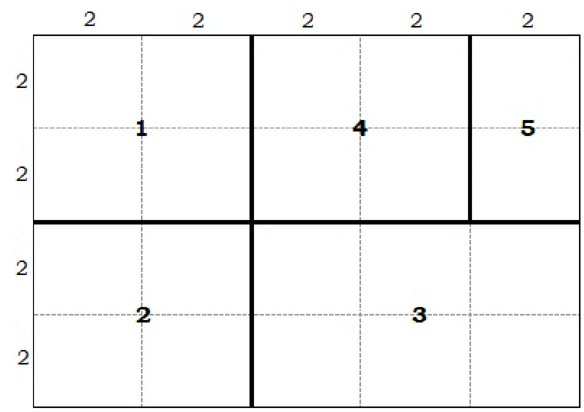

Figure 5 Layout after the 1st iteration

The centroids and the distance matrices are regularly updated. Detailed calculation process is skipped. Six interchanges are possible in the 2nd iteration. All of them are listed in Tab. 2, including the cost results. The interchange pair is 1 and 4 (169 is less than 181).

Table 2 Exchange pairs and exact total transport costs (iteration 2)

Pair	1-2	1-4	2-3	2-4	3-4	3-5
C_{tr}	181	**169**	215	181	187	177

Layout after the iteration 2, C_{tr} = 169, see Fig. 6.

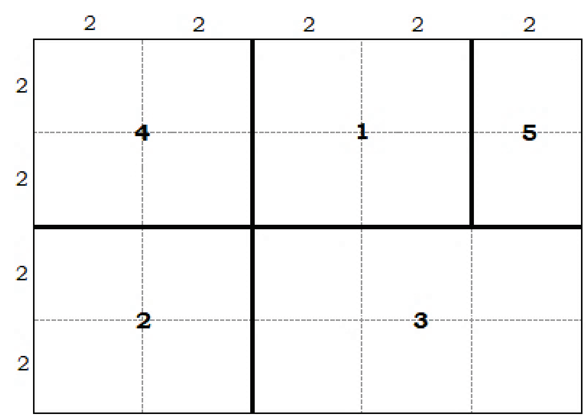

Figure 6 Layout after the 2nd iteration

The centroids are:

$(X_1, Y_1) = (6, 6)$, $(X_2, Y_2) = (2, 2)$, $(X_3, Y_3) = (7, 2)$, $(X_4, Y_4) = (2, 6)$, $(X_5, Y_5) = (9, 6)$.

The centroids and the distance matrices are updated for each interchange. In the third iteration, six interchanges are possible (Tab. 3). The interchange pair is 3 and 5 (165 is less than 169).

Table 3 Exchange pairs and exact total transport costs (iteration 3)

Pair	1-2	1-3	1-5	2-3	2-4	3-5
C_{tr}	169	190	202	221	185	**165**

Layout after the iteration 3, C_{tr} = 165, see Fig. 7.

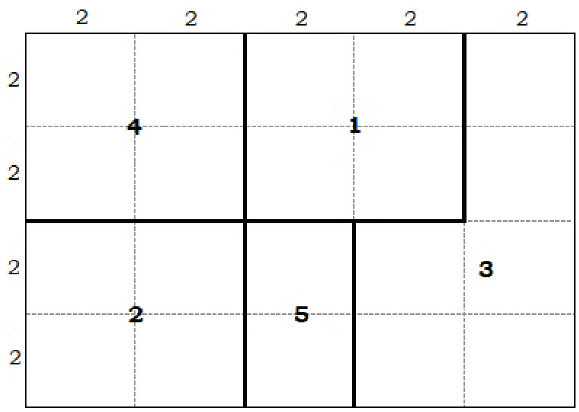

Figure 7 Layout after the 3rd iteration

The centroids are:

$(X_1, Y_1) = (6, 6)$, $(X_2, Y_2) = (2, 2)$, $(X_3, Y_3) = (8.33, 3.33)$, $(X_4, Y_4) = (2, 6)$, $(X_5, Y_5) = (5, 2)$.

Fourth iteration: at this stage, six interchanges are possible (Tab. 4). The interchange pair is 1 and 5 (148 is less than 165).

Table 4 Exchange pairs and exact total transport costs (iteration 4)

Pair	1-2	1-3	1-4	1-5	2-4	2-5
C_{tr}	170	205	177	**148**	175	189

Layout after the iteration 4, C_{tr} = 148, see Fig. 8.

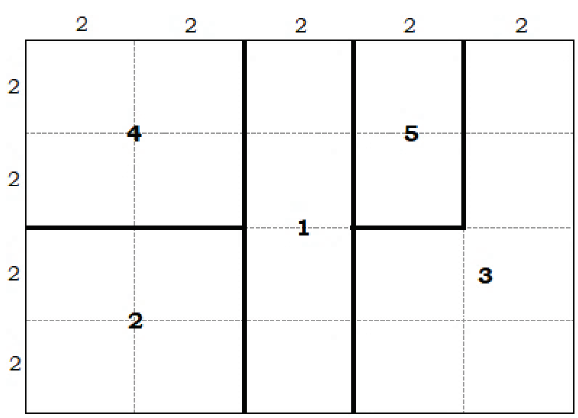

Figure 8 Layout after the 4th iteration (final layout)

The centroids are:

$(X_1, Y_1) = (5, 4)$, $(X_2, Y_2) = (2, 2)$, $(X_3, Y_3) = (8.33, 3.33)$, $(X_4, Y_4) = (2, 6)$, $(X_5, Y_5) = (7, 6)$.

In the fifth iteration five possible interchanges give worse results (see Tab. 5).

Table 5 Exchange pairs and exact total transport costs (iteration 5)

Pair	1-2	1-3	1-4	2-4	3-5
C_{tr}	154	180	163	150	157

The cost of the best layout (150) is not less than the cost of the last layout (148).

The last layout is the final layout. The total transport cost is 148 (28 % less than the initial 205). Department 3 was given a non-rectangular shape.

5 DISCUSSION

The CRAFT algorithm and our modified algorithm are heuristic programmes. They usually provide different solutions to a problem if different initial layouts are available. The literature [16] recommends using no less than three initial layouts as starting procedures. Neither algorithm guarantees an optimal solution. In practise, the limit for layout optimisation has been set at 50 workplaces or departments.

We can interchange workplaces of different sizes, which can lead to very irregular shapes of workstations that may be unusable in practise. Using area centroids to measure distances between workstations is not always realistic (especially for non-rectangular shapes).

To improve the CRAFT algorithm for layout optimisation, several additional improvements can be explored. Incorporating modern heuristic or metaheuristic methods, such as genetic algorithms or particle swarm optimisation, could improve its ability to find near-optimal solutions for complex plant layouts. Adding machine learning techniques could also enable adaptive decision-making based on historical data and contextual factors and further optimise results. Improving the algorithm’s ability to handle dynamic and multi-criteria problems could make it even more versatile.

In the given benchmark example [15], the CRAFT algorithm yielded a saving of 12 % in transport costs, while our modified algorithm yielded a saving of 28 % (the value 181 was reduced by a further 18 % to 148, i.e. the result of the CRAFT algorithm is 22 % worse than with the modified algorithm). Our algorithm never delivers a worse result due to its exact calculation.

6 CONCLUSION

Regardless of the type of production (or provision of services), we have four criteria for evaluating the results: quality, quantity, time and cost. The layout of workplaces (or departments) has a significant impact on these criteria, as it promotes quality improvement, stabilises quantities and time consumption and reduces costs. Therefore, we consider the layout of an organisation as a strategic decision for sustainable operation.

The complexity of today's factories requires the use of advanced computer tools for system analysis and design, such as simulation and optimisation. The latest trends are moving towards digital twins of the factory with 3D visualisation and real-time simulations.

In this article, we have shown an improvement of the CRAFT algorithm used for layout optimisation. We decided to make a simple, conventional improvement to the algorithm. With the presented modification of the algorithm we achieve much better optimisation results than with the basic method, with more intensive calculations (weakness) and exact values (advantage). This is also demonstrated using a practical example.

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