CONFERENCE ON PRODUCTION SYSTEMS AND LOGISTICS
CPSL 2021

2nd Conference on Production Systems and Logistics

A two-stage Tabu Search for multi-objective facility layout problem

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Abstract

In this paper, a new solution for the facility layout problem is presented. The approach was integrated into a planning software. The aim of the MeFaP research project was mainly the development of a user-friendly decision support regarding the facility layout problem for small and medium-sized companies. Therefore, a realistic modelling of the planning problem was focused on. Thus, a path planning with area allocation was integrated, for example. The metaheuristic Tabu Search was selected as a solution approach. To ensure an efficient optimisation, the optimisation is performed in two steps, once without and then with route planning. The experiments were performed with the objectives material flow distance, temperature and cleanliness, which are briefly described. The results of the experiments were compared with current solution approaches.

Keywords

multi-objective facility layout problem; factory planning; multi-criteria optimization; metaheuristic; tabu search; planning software

1. Introduction

In the research project MeFaP, an optimization approach for quantitative, multi-criteria facility layout planning was developed [1–3]. More precisely for the facility layout problem (FLP), which is defined as the arrangement of facilities in a factory site, to achieve the best possible fulfilment of objectives while taking restrictive constraints into account. The project aimed to provide an user-friendly decision support for non-professional users. Furthermore, quantitative layout evaluation formulas, which were developed in the preliminary project QuaMFaB [4], were examined regarding their applicability for a multi-objective facility layout problem. Since currently used optimization approaches are mostly limited regarding their objective function. Often only one objective is optimized, the material flow distance respectively material handling costs (cf. [5]). A comprehensive survey of current approaches is given by DRIRA ET AL., HOSSINI-NASAB ET AL. as well as SHARMA AND SINGHAL [6,5,7]. In facility layout planning, however, other objectives respectively objective fields, such as changeability, communication flow or occupational health and safety standards (like temperature and cleanliness), are in many cases also relevant for planning (cf. [9,8]). For this reason, a multi-criteria solution approach was developed to enable holistic optimization of facility layouts. Due to the structure of the evaluation formulas, a discrete layout presentation was necessary (cf. [4]). This means that the factory floor is covered by a grid of square cells with equal size, which is variable and can be adapted by the user, to model specific planning projects. The facilities are also covered with the grid. In this way, different information can be assigned to individual cells of the factory floor or facilities. For example, the availability of a medium such as electricity or the lighting intensity of daylight can be assigned to a cell of the factory floor. A corresponding demand can be assigned to the cells of a facility. By positioning a facility on the grid, the superimposed cells are linked together. The layout is evaluated by comparing the demand of the facility cell and the supply of the factory floor cell. Due to the discrete representation, the

DOI: https://doi.org/10.15488/11302

FLP is modelled as a quadratic set covering problem (QSP). The facilities are characterized by a regular shape and a fixed aspect ratio. In addition, the facilities have fixed pick-up and drop-off points as well as spatial orientation. Overlapping of facilities is not allowed. The optimization problem is also characterized as an open field layout. During the optimization, the position of the facilities and the necessary path structure for the layout is arranged.

According to prevailing opinion in the literature, a continuous problem formulation is better suited to find an optimal solution for the FLP than a discrete problem formulation [6,10]. Due to the grid-based problem formulation, facilities could not be represented with their exact size, and have to be adapted to the cell size of the grid. This usually leads to an (slight) enlargement of the facilities. Because of the insufficient detailing, it might not be possible to consider exact pick-up and drop-off points [6]. Thereby a path planning is also shown as not possible. As the main disadvantage of a discrete problem formulation, it is argued that the "real" optimal respectively continuous position of the facilities cannot be found because of the limited solution space [12,11].

This argumentation ignores the fact that the level of detail depends on the definition of the cell sizes. As smaller the cells are, as greater the detailing is. Furthermore, it is neglected, that the often-used fixed size and shape of facilities is based on the assumption, that this information is known a priori. In the research project, all assumptions were verified with manufacturing companies. According to the predominant opinion of the companies, a fixed representation of facilities is sufficient in the phase of block layout planning. Because the final design of the facilities is done in the subsequent realization planning. Accordingly, an approximate positioning of pick-up and drop-off points is also sufficient, since these points are also finalized in a later planning step. BOCK AND HOBERG provide a realistic layout planning with a discrete approach, where paths are considered [13].

Within the project, a decision was made against a continuous problem formulation. In existing continuous approaches, pick-up and drop-off points as well as paths are taken into account [5,11]. However, the paths usually pass along the outer edges of the facilities or a rectangular path routing is assumed, whereby paths in some cases even cross trough other facilities [14,12]. The necessary path area is often not considered in the layout [16,15]. Consequently, an optimal positioning of the facilities is achieved, but this is not realizable without considering the path area. Therefore, current approaches are often not suitable for realistic layout planning. KLAUSNITZER ET AL. provide a continuous approach, in which path areas are planned [14].

In the project, a decision support system should be developed that suggests companies the most optimal, but also realistic layout variants. As mentioned before, the discrete layout representation was necessary to integrate the previously developed evaluation formulas. This can be realized with the chosen approach.

2. Optimization Approach

This paper presents an optimization approach based on the metaheuristic tabu search. In the following, the implementation of tabu search, as well as the associated procedures for neighbourhood search, are presented. Furthermore, the objectives are explained. First, the problem formulation is explained in more detail. In the description of the optimisation approach, the developed software is also referenced. For example, user input will be described. Figure 1 shows the basic process of optimization.

2.1 Implementation of the problem representation

For discrete problem formulation, the factory surface is covered by a grid of square cells of equal size. The size of the cells can be defined by the user in integer steps. The shape of the factory floor can be modelled by hiding cells. In this way, non-regular shapes can also be represented.

Restrictions can be assigned to each cell of the factory floor. These include ceiling height, floor load, ceiling load. Additionally, information regarding media can be assigned to the cells. Media do not represent restrictions during the optimization but can be used as an objective. The number of media can be defined by the user (e.g. the availability of water, electricity, or compressed air). Furthermore, restrictive areas can be defined for different types of facilities or departments (e.g. production, assembly, warehouse). If one or more restricted areas have been defined for a facility type, it is only possible to position the associated facilities in this area. If no restrictive area is defined, facilities can be positioned anywhere, even in restrictive areas of other facility types. Additionally, it is possible to position fixed path cells.

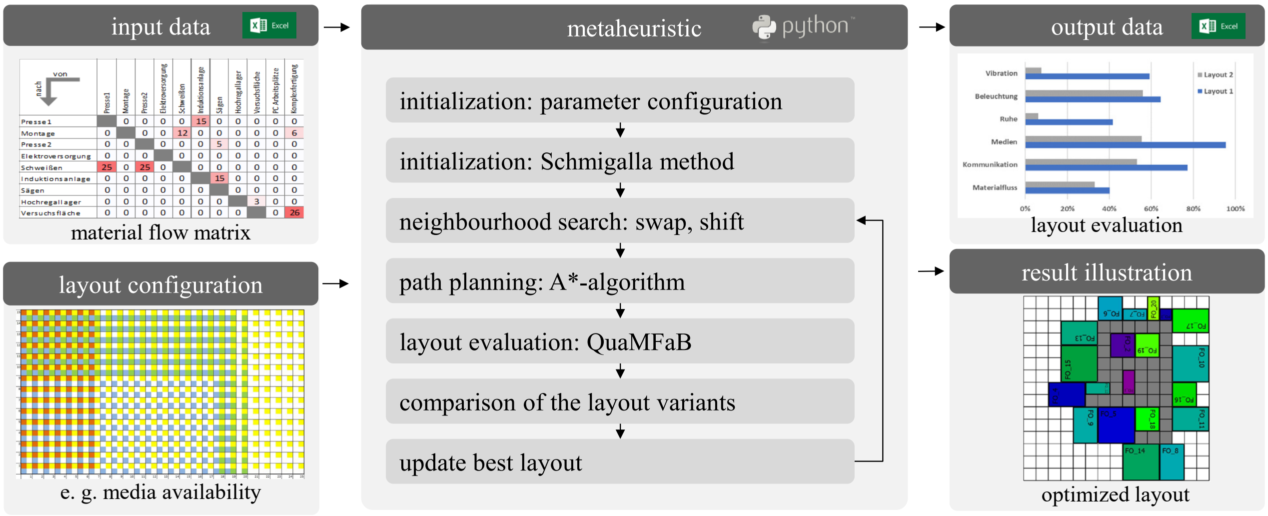

Figure 1: abstract optimisation process

The position of the facilities in the layout is defined by their upper left corner. Facilities can be rotated in four steps (0°, 90°, 180°, 270°). Furthermore, it is possible to mirror facilities on the vertical axis. Rotation and mirroring affect the position of pick-up and drop-off points in the layout. The definition of pick-up and drop-off points is also done by the user within the setup. When positioning is not performed, pick-up and drop-off points are placed in the upper left corner at a rotation of 0°. The position of facilities in the factory floor can be fixed by the user. For example, machines with special fundaments could be considered in planning without changing their position. The fixing was a requirement of the consulting companies.

2.2 Metaheuristic

Tabu Search (TS) is a local search technique developed by GLOVER [17]. The method is based on the tabu setting of transformation steps. A transformation step is the repositioning of a facility in the layout. With an iteration of the tabu search, a repositioning is done for each facility. This means that as many new layouts are created as there are facilities. In an iteration, the same neighbourhood search method is performed for all facilities. This is a partial search in the neighbourhood. The best transformation step is accepted as new solution, set as tabu, and added to a tabu list. If a transformation step subsequently leads to the best solution in the neighbourhood again, it is not selected, but the next best neighbour is selected. The length of the tabu list (*TL*) controls how long a solution remains tabu. When the tabu list is full, the oldest entry is deleted. The tabu list avoids circling around a local optimum. If a tabu neighbour is better than the best-known solution, the tabu mechanism is bypassed; this is a so-called aspiration criterion.

2.3 Initialization

Two initialization methods were implemented. An adaptation of the Schmigalla method and a random based positioning. During the initialization, only feasible layouts are generated. Accordingly, all restrictions are strictly respected. If it is not possible to position a facility during initialization, the layout is deleted, and the method is executed again. The user can select the initialization method. Various experiments have shown that the random-based method is more likely to generate a valid initial layout when a high degree of space utilization is given.

In the adaptation of the **Schmigalla method**, first, the order of the facilities is determined based on their material flow relations. Then the first facility is positioned in the middle of the factory floor. Subsequently, it will be tried to arrange the next facility to the left, right, above or below the previously positioned facility. The direction is selected randomly. This process is repeated until all facilities are positioned.

At the beginning of the **random-based initialisation**, the facilities are sorted in descending order according to their surface area. Based on this sequence, the facilities are placed at a random position. Rotation and mirror are also randomly selected. Since the largest facilities are positioned first, it is reliable to find a feasible solution even with a high space utilization ratio.

2.4 Neighbourhood search methods

Two neighbourhood search (NHS) methods were implemented. The selection of which neighbourhood search method is used in the optimization can be controlled by the user. For this purpose, a distribution can be set, which must sum up to 100%. During the optimization, a random number between 0 and 1 is chosen, the NHS is selected by comparing it with the distribution.

The first method is an adaptation of the **Local Reallocation Search** (LRS) by Bock und Hoberg [13], which tries to reposition a randomly selected facility at a random position nearby. The rotation and mirroring of the facility are also determined randomly. If a check confirms that all restrictions are met, the facility is positioned, and the method is left. If restrictions are violated, a new random position, rotation and mirroring are chosen and checked again. This procedure repeats until an a priori set iteration maximum is reached ($LRS_{Iteration}$). By default, this is set to 100 iterations, however, it can be changed by the user. If the iteration maximum is reached, a new facility is randomly selected, and the process starts again. The maximum permissible distance to the original position is used as a control parameter of the LRS ($LRS_{StepSize}$). By default, the value is set to 10 cells and can also be changed by the user. Good results are achieved if the value reflects approximately the edge length of a medium-sized facility related to the data set.

In the **Open Area Search** (OAS), a facility is randomly selected first. Then the size of all open areas in the layout is calculated in which the selected facility could fit in. The selection of the open area can be performed in two different ways. In the first variant, the determined open areas are sorted in descending order of size. This is an attempt to prevent large open areas from being occupied by small facilities. In the second variant, the open areas are sorted in ascending order concerning the distance to the current position of the facility. After sorting, the method checks if the facility could be positioned with respect to the restrictions. If this is the case, the facility is repositioned, and the method is left. If restrictions would be violated, the next open area from the list is checked. If no suitable open area is available, a new facility is randomly selected, and the process starts again. Figure 2 shows the application of the OAS concerning facility $f = 3$, with the size-oriented sorting variant. In this example, open area$_3$ would be selected first for the check.

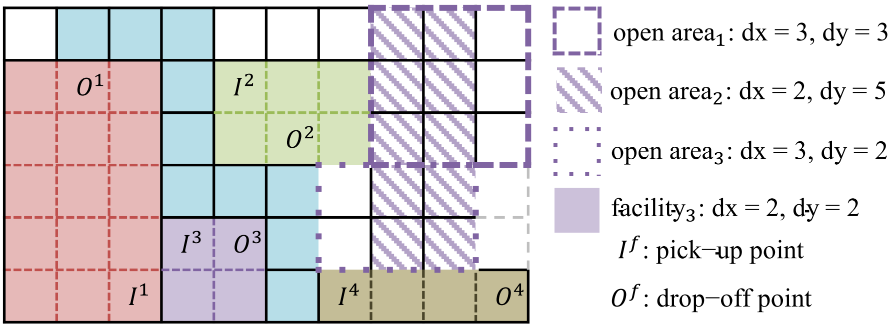

Figure 2: Example of possible open areas for facility $f = 3$

2.5 Path planning

Two methods were used to calculate the transport path length, the A* algorithm and the Euclidean distance. The **A* algorithm** is a well-known and frequently used shortest path algorithm first published by Hart et

AL. [18]. Compared to other shortest path algorithms, it requires less computing power and memory. The A* algorithm always finds the shortest path between two points. In the present case, this concerns the pick-up and drop-off points of the facilities between which a material flow is necessary. Free cells, fixed path cells and local path cells are available for path planning. Local path cells are cells that have already been used by a path between other facilities. These are accordingly planned in the layout. The use of various cell types has different "costs". The default values of the route costs are: fixed route cells = 1, local route cells = 1.5 and free cells = 3. Accordingly, the A* algorithm would take a diversion of 3 cells to use fixed route cells instead of free cells. It always determines the shortest respectively the cheapest path. In this way, it is avoided that multiple parallel paths are created in the layout. Path costs can also be modified by a user.

The **Euclidean distance** is the direct connection between two points. If the Euclidean distance is used to calculate the transport path lengths, local path cells are not planned in the layout. The calculation of the method is many times faster than the A* algorithm.

2.6 Two-stage optimization

In order to reduce the computing times, a two-stage optimisation was implemented. The functionality of the applied heuristics is not affected. The acceleration is mainly based on the selection of the path planning approach. In the first optimisation stage, the Euclidean distance is used to calculate the transport path lengths. In the second stage, the A* algorithm is used. In this way, about 10 to 15 times more layout variants can be evaluated at the same time. The control parameters of the optimisation stages can again be set by the user. These should be selected in such a way that the first stage takes up a much larger share of the total computing time. During the experiments, a ratio of 20:1 was chosen.
Between the stages, the layout must be re-initialised to enable path planning with the A* algorithm. This is because, in the first stage, the pick-up and drop-off positions of the facilities can be blocked by other facilities or the external walls of the factory. This is not possible when using the A* algorithm, because otherwise no path can be found. The intermediate initialisation of the layout is based on the Local Reallocation Search, trying to place the facilities at the same position as before. In contrast to the behaviour with the Neighbourhood Search, the positioning is not random, instead, it moves outwards step by step from the original position. Rotation and mirroring are also not randomly but systematically varied.

2.7 Layout evaluation

The evaluation of the layout variants is based on the evaluation formulas designed in the preliminary project [4]. These were adapted or improved in the current project [1]. Scaling of the objectives is not necessary. The result values of all evaluation formulas are percentage values with a value range of $\{0, 100\}$. This results from the comparison of layout variants. An intermediate evaluation result of a current layout variant is compared with the best-known intermediate evaluation result of the respective objective. The best-known evaluation result is constantly updated during the optimisation process if there is a better solution. This modelling ensures direct comparability or transferability. The modelling also allows the combination of objectives that have to be minimised and maximised. However, a weighting factor ω is applied to the combination. It can also be configured by the user. In the following, only the evaluation formulas relevant for the paper are presented.

f: facility
m: material flow between a pair of facilities
v: layout variant

Material flow distance

$$MF_v = \left(\frac{MFd_{min}}{MFd_v}\right) \cdot 100\% \qquad (1)$$

MF_v: objective function of the material flow distance for variant v
MFd_v: material flow distance of variant v in metres
MFd_{min}: minimum material flow distance of all variants

$$MFd_v = \sum_{m=1}^{M}(MFI_m \cdot d_m) \tag{2}$$

d_m: distance of material flow m in metres
MFI_m: transport intensity of material flow m

Temperature
The objective temperature is an objective function which must be maximised. Thus, influencing facilities should be positioned separately from each other. For this purpose, a temperature factor TE_f is assigned to each facility. The factor is freely selectable but must follow a predefined scheme: positive values represent temperature emission, zero means neutrality and negative values indicate temperature sensitivity. The more the values of two facilities differ, the greater is the distance requirement (4). Dependencies must be indicated with a sign change.

$$Temp_v = \left(\frac{Tempd_v}{Tempd_{max}}\right) \cdot 100\% \tag{3}$$

$Temp_v$: objective function of the temperature-sensitivity in variant v
$Tempd_v$: temperature-sensitive distance of variant v
$Tempd_{max}$: variant v with the maximum temperature-sensitive distance

$$Tempd_v = \frac{1}{2} \cdot \sum_{f=1}^{F} \sum_{f\prime=1}^{F\prime} \left(\left| TE_f - TE_{f\prime} \right| \cdot \sqrt{\left(x_{Cen_f} - x_{Cen_{f'}}\right)^2 + \left(y_{Cen_f} - y_{Cen_{f'}}\right)^2} \right) \tag{4}$$

x_{Cen_f}, y_{Cen_f}: centroid-coordinate of facility f TE_f: temperature factor of facility f
$x_{Cen_{f'}}, y_{Cen_{f'}}$: centroid-coordinate of facility f‘ $TE_{f\prime}$: temperature factor of facility f'

Cleanliness
The functionality of the objective function is similar to the objective function of temperature. Accordingly, the cleanliness factor CE_f represents the same dependencies as the temperature factor TE_f.

$$Clean_v = \left(\frac{Cleand_v}{Cleand_{max}}\right) \cdot 100\% \tag{5}$$

$Clean_v$: objective function of the cleanliness-sensitivity in variant v
$Cleand_v$: cleanliness-sensitive distance in variant v
$Cleand_{max}$: variant v with the maximum cleanliness-sensitive distance

$$Cleand_v = \frac{1}{2} \cdot \sum_{f=1}^{F} \sum_{f'=1}^{F'} \left(\left| CE_f - CE_{f'} \right| \cdot \sqrt{\left(x_{Cen_f} - x_{Cen_{f'}}\right)^2 + \left(y_{Cen_f} - y_{Cen_{f'}}\right)^2} \right) \tag{6}$$

x_{Cen_f}, y_{Cen_f}: centroid-coordinate of facility f CE_f: cleanliness factor of facility f
$x_{Cen_{f'}}, y_{Cen_{f'}}$: centroid-coordinate of facility f' $CE_{f\prime}$: cleanliness factor of facility f'

3. Case Study

For the experiments, an in the literature frequently used data set was analysed [20,21,19,12]. It was first introduced by IMAM AND MIR [22]. The data set contains 20 facilities. The material flow relationships were adopted without any adjustments. For the objectives temperature and cleanliness the data set was extended by randomised attributes (see Table 1). The cell size was set to 5 metres, which corresponds to a transport route with two-way traffic and an additional pedestrian path. The shape of the factory floor area is square and has an edge length of 75 metres. Accordingly, the grid has 15x15 cells. The pick-up and drop-off points were placed in the upper left corner of the facilities. Except for the facilities that have an edge length of more than three cells. In these, pick-up and drop-off points were placed in the middle of one side. For the control parameters of the optimisation a sensitivity analysis was performed. The resulting control parameters are shown in Table 2. The two-stage optimisation required an average of about 2 hours of computing time.

Table 1: Extended facility data

facility	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
TE_f	1	-1	0	0	0	1	1	1	1	1	0	1	-1	-1	0	-1	0	0	-1	-1
CE_f	0	1	1	1	0	-1	0	0	0	0	1	-1	0	0	-1	0	-1	1	-1	-1

Table 2: Parameter setting

control parameter	first stage	second stage
TL – length of tabu list	10	7
$TS_{Iteration}$	2.000 - 10.000	100
NHS-distribution	0.8 LRS; 0.2 OAS	0.8 LRS; 0.2 OAS
$LRS_{StepSize}$	5	5
$LRS_{Iteration}$	100	100
rotation of facilities	enabled	enabled
mirroring of facilities	enabled	enabled

First, an independent optimisation was performed for each objective. Then multi-criteria optimisations were executed. If two objectives were used, the weighting factors were set to 0.5 each, i.e. equal weighting. For the optimisation of all three objectives the weighting factors were chosen as follows: material flow $\omega_{MF} = 0.4$, temperature $\omega_T = 0.3$, cleanliness $\omega_C = 0.3$. The results of the experiments are shown in Table 3. Figure 3 a) shows the resulting layout regarding the mono-criteria optimisation of the material flow distance. For the mono-criteria optimisations the best result was achieved concerning the respective objective. In the multi-criteria optimisations, as previously expected, a deterioration of the results occurs, because of the contradictory objectives. When analysing the objectives, it is important to remember that the material flow distance (MF_v) must be minimised, and the temperature ($Temp_v$) and cleanliness ($Clean_v$) maximised. However, the results demonstrate that multi-criteria optimisation leads to an acceptable trade-off between different objectives. Thus, the aimed holistic approach for layout optimisation was achieved.

Table 3: Experimental results

	$MF_{v=best}$ (metres)	$Temp_{v=best}$	$Clean_{v=best}$
$\omega_{MF} = 1$	**12,860**	5,654	5,282
$\omega_T = 1$	32,210	**10,845**	8,222
$\omega_C = 1$	35,170	8,975	**9,932**
$\omega_{MF} = 0.5$, $\omega_T = 0.5$	16,160	8,083	6,929
$\omega_{MF} = 0.5$, $\omega_C = 0.5$	16,200	7,595	6,760
$\omega_T = 0.5$, $\omega_C = 0.5$	35,950	10,753	9,451
$\omega_{MF} = 0.4$, $\omega_T = 0.3$, $\omega_C = 0.3$	17,830	8,838	7,320

The results regarding the material flow distance were compared with other solution approaches [20,21,19]. The presented solution approach leads to similar good results (see Table 4). However, as the other solutions were optimised without a path structure and with pick-up and drop-off points in the centre of the facilities, the layouts had to be readjusted. A manual attempt was made to reproduce the arrangement of the facilities, considering path structure and discrete layout representation. For example, Figure 3 b) shows the adjustment concerning the result of GONÇALVES [21]. The adjustment to the path structure is expected to lead to a deterioration of the objectives. Therefore, the comparison must be examined critically.

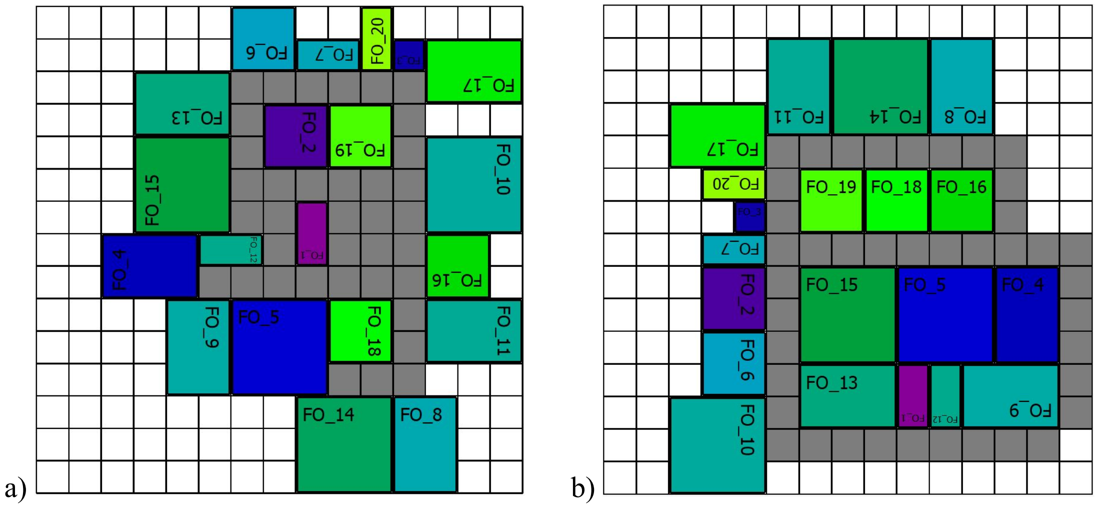

Figure 3: a) best result of MeFaP (ω_{MF} = 1), b) transmitted layout from GONÇALVES [21]

Table 4: Comparison of results with other solution approaches regarding material flow distance (*MF*)

$\omega_{MF} = 1$	MeFaP	[20]	[21]	[19]
$MF_{v=best}$ (metres)	12,860	21,510	16,420	19,320

4. Facility layout planning software

The previously described solution approaches were implemented with python. Additionally, a user interface was developed (Figure 4). With the resulting software, companies are able to optimise layouts independently.

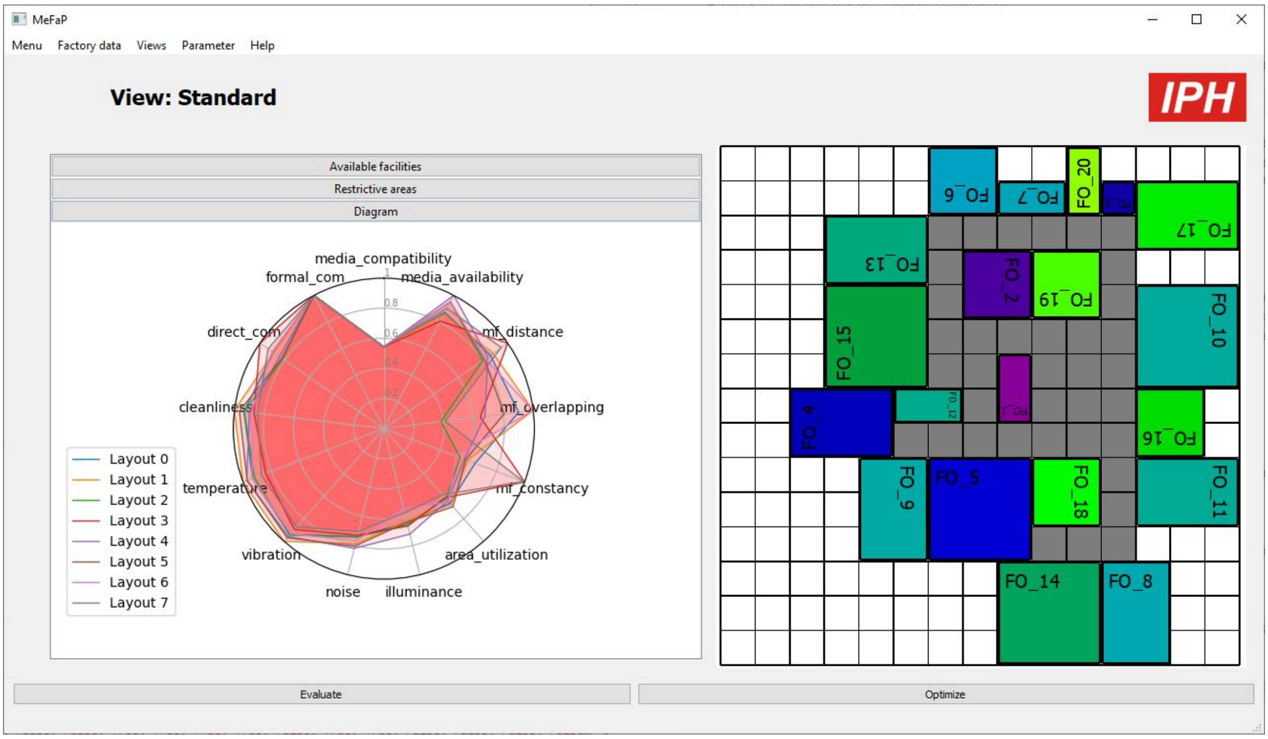

Figure 4: Example of the graphical user interface

The input data (e.g. facility data, media, material flow relationships) can be prepared in an Excel file and imported into the software. In future, it will be even possible to automatically capture facility data [23]. Factory floor space, restrictions and media availability can be planned in the software. Besides optimisation, manual planning and evaluation is also possible. In this way, existing layouts can be analysed. In addition, optimised layouts can be modified by a user and re-evaluated. The software is available as a free download (mefap.iph-hannover.de). The code is open source (gitlab.com/iph-group/lo_aif_mefap_2017/mefap).

5. Conclusion

In this paper a new solution approach and software for the facility layout problem was presented. The focus of the research project was not the development of a solution approach that is as powerful as possible, but rather to provide an easy decision support for companies. As is often the case with decision support applications for real problems, subsequent changes may be necessary, for example, to create a layout that is natural to the human eye. However, this does not mean that restrictions are not considered during the optimisation. The implemented heuristic approach is nevertheless suitable to create good layouts. The comparability with existing solution approaches could be proven. However, future improvements are possible. For example, additional solution approaches can be implemented in the software. The required computing time should be reduced by more efficient coding. The user-friendliness of the software may be improved continuously in cooperation with companies.

Acknowledgements

The IGF-Project 19666 N of the Bundesvereinigung Logistik e. V. is funded by the German Federation of Industrial Research Associations within the funding programme of Industrial Collective Research of the Federal Ministry for Economic Affairs and Energy based on a resolution of the German Bundestag.

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Biography

Paul Aurich (*1991) studied industrial engineering at the Otto-von-Guericke-University Magdeburg, focused on mechanical engineering and logistics. Since November 2017 he has been working at IPH – Institut für Integrierte Produktion Hannover gGmbH as a project engineer in the field of logistics. In research and consulting projects he deals with factory planning and operations research.

Marc Speckmann (*1997) studied computer science at the Leibniz University Hannover. Since October 2019 he has been working at IPH – Institut für Integrierte Produktion Hannover gGmbH as a research assistant. In research projects he deals with factory planning and software development.

Christian Böning (*1984) has been working as project engineer in the field of logistics at IPH - Institut für Integrierte Produktion Hannover gGmbH since 2011. In research and consulting projects he deals with energy cost-oriented machine scheduling and factory planning. Since August 2013 he is head of the logistics department.

Malte Stonis (*1979) is managing director of the IPH – Institut für Integrierte Produktion Hannover gGmbH. His research focuses on increasing the efficiency and digitization of production.