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# Advanced Scientific Algorithms in Digital Factory Design Applications

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*In contrast to manual procedures, research constantly develops modern computerized factory design approaches applying concepts of Industry 4.0. Nevertheless, literature hardly reveals their practical application. A market review analyzing recent software applications shows that they still focus on simple and outdated algorithms, resulting in limited support for facility arrangement. This study further analyzes the use of scientific approaches implemented in software applications for factory design and suggests new research directions to increase their practical applicability. Therefore, we conducted a semi-structured interview study investigating four layout design software developers. Applying an iterative approach, semi-structured and guided interviews were performed, coded, grouped into categories referring to similar phenomena, and interpreted to provide proposals for future research. The results indicate that innovative, automated methods are met with skepticism, although their performance is considerably superior to traditional approaches. The interviewed developers for factory design software reveal certain features they expect from modern approaches emerging from research to ensure successful implementation.*

**Keywords:** Factory layout design; Software applications; Metaheuristics; Interview study

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## 1 Introduction

Manufacturing companies are constantly faced with major challenges shaping their requirements for success, such as new production technologies, shorter product life cycles, as well as frequent changes in market dynamics. Certain situations may compel companies to make major changes to their manufacturing sites, affecting the arrangement of facilities and equipment in the plants. This common problem is referred to as the ”facility layout problem” (FLP) in literature. There is substantial prior research starting from the 1960s (Anjos and Vieira, 2007).

During the last decades, a trend towards metaheuristics and algorithm-based optimization of the arrangement problem has evolved (Ahmadi et al., 2017). Nevertheless, the practical application of scientific methods, particularly their software implementation, within design projects is scarcely mentioned. However, in the context of Industry 4.0 and Smart Manufacturing, advanced software applications are gaining importance throughout all subject areas in manufacturing companies and constitute a worthy area for optimization and further research (Bracht et al., 2018).

In a recent paper, Klausnitzer et al. (2017) conducted a case study to investigate the application of scientific algorithmic methods in practice. Users of software applications, consulting engineers in this case, and a scientific institute specialized in factory design were interviewed. Their key findings are that advanced mathematical methods are not applied to factory design projects due to the users' unawareness of extant superior methods and lack of algorithmic support regarding the applied software solutions. These findings add impetus to the research of this paper.

Whereas Klausnitzer et al. (2017) focused on users of factory design applications, we suggest that investigating developers of factory design applications might produce interesting findings. It can be safely presumed that the developers of software applications in digital factory design have a profound knowledge of methods and trends in their field of interest and have a high affinity for scientific methods. To the best of our knowledge, there is no empirical research on the approach applied by software engineers to develop the applications as well as the impact of scientific research on these development procedures. Furthermore, the evolving trend towards metaheuristics has produced various scientific algorithms for the FLP that produce promising results but little is known about the value the software developers for factory design applications give these algorithms.

Therefore, this paper aims to answer the following research questions using a market review followed by a multiple semi-structured interview study:

- How do modern software applications methodically support the factory design process?
- How does scientific research affect developers of those applications?
- Why are advanced scientific algorithms adopted by software developers for factory design?

Our contribution is two-fold: From a theoretical standpoint, we provide insights from practice, in particular the needs and wishes that software developers have regarding scientific methods to encourage their implementation in factory design applications. Researchers are able to focus on specific aspects that will make their methods usable outside of the field of research. From a practical standpoint, we aggregate the recent developments in science and highlight important future developments as noted by leading representatives of software developing companies.

The remainder of this paper is organized as follows. Section 2 provides a brief overview of the literature concerning solution methods for the facility arrangement and digital factory design applications. Section 3 describes the methodology adopted for the empirical research. Section 4 presents the findings from the market review as well as the interview study. Section 5 provides recommendations for practice, section 6 our conclusions. The limitations of the study and opportunities for future research are discussed in section 7.

## 2 State of Research

The basic process of factory design as defined in VDI (2011) or Grundig (2015) consists of the following planning phases: Target planning, concept planning, detailed planning, execution planning, and implementation. A large amount of research considering the FLP focuses on the concept and detailed planning phases, where several layout variants are generated to minimize the material handling effort as a function of travel distances. The first steps include determining the functions of facilities, dimensioning of required areas, and the arrangement of the facilities within the area. Subsequently, the block layout variants need to be refined with real life requirements considering structural conditions like walls and pillars, as well as ergonomic and logistic requirements. Favored layout variants are then designed according to specific conditions and restrictions such as facility details and orientation.

The step of arranging the facilities can be reduced to an algorithmic process that solves an optimization problem as it depends on material flow intensities and closeness ratings (Drira et al., 2007; Tompkins et al., 2010). Popular procedural approaches for factory planning and solving the FLP (e.g. Schenk et al., 2014; Grundig, 2015) still focus on outdated and simple algorithmic methods, such as the approaches of Schwerdtfeger (Kettner et al., 1984) and Schmigalla (Schmigalla, 1968). These methods illustrate flow relationships between functional areas to arrange them according to a determined pattern. Specific facility areas and real-life requirements are taken into account subsequently. The solution quality largely depends on the experience of the layout planner as well as trial-and-error.

Other approaches to solve the FLP are mathematical methods that lead to optimal solutions. However, the FLP is known to be NP-hard (Garey and Johnson, 1979), resulting in computational intractability for most of the practical problems, due to the large number of facilities to be arranged. This led to the emergence of heuristics and, more recently, metaheuristics, such as genetic algorithms, tabu searches, or simulated annealing. They are suitable for large problems that can be solved in a short time with solution qualities near the optimum, although the optimum cannot be guaranteed (Drira et al., 2007). In contrast to the traditional methods, modern approaches consider a variety of requirements like area constraints, material handling points, path design, and multiple floors in one single step. A concurrent approach to the arrangement of facilities and the design of real life requirements can significantly improve the quality of the layout solutions and the productivity of the user. Within a short time, several layout variants can be generated and evaluated without the follow-up work or a costly replanning of infeasible layouts obtained during a sequential process.

To support the design process for the FLP there are several factory design software applications. The selection of the suitable software application depends on the specific problems, data, information and defined goals (Schenk et al., 2014). In the context of Industry 4.0/Smart Manufacturing, advanced applications supporting the ”digital factory” are entering the market. Digital factory is a network of digital models, methods, and tools integrating a continuous data management system that aims for holistic planning, evaluation, and improvement of structures, processes, and resources of a factory.

It allows for collaborative planning to consider the experience of various users, which further contributes to an improvement of solution quality and approval (VDI, 2008). The digital factory applications can be categorized into three main groups that are briefly presented in the following:

**Tools for visualization:** CAD (Computer Aided Design) tools are used to visualize facility layouts and draft well-detailed drawings that are easy to create and to change in a short time. CAD tools are widely utilized in all kinds of manufacturing companies worldwide. However, standard applications like AutoCAD rarely provide scientific methods to support the layout design procedure (Grundig, 2015).

**Simulation tools:** Simulation tools are used to study the dynamic interrelations of manufacturing systems. The manufacturing system can be optimized by creating and analyzing different variants to select the best alternative (Arnold and Furmans, 2009). In recent years, CAD tools have been coupled with simulation tools to create layouts based on CAD data directly using standard 3D components. The complexity of the software applications and the needed expertise to generate a coherent representation of the real process flow from a static visualization is still one of the main challenges of simulative factory design (Schenk et al., 2014).

**Virtual reality tools:** Intuitive applications like virtual reality and augmented reality tools are receiving an increased interest regarding layout design. They are able to construct a direct or indirect view of real-world environments augmented with additional haptic or visual information (Schenk et al., 2014). 3D modeling and optimization of whole factory floors is simplified. So called ”participative planning tools” combine two-dimensional representations as in CAD tools with three-dimensional representations for a better visual experience and cooperative collaboration in project teams. In addition, users are provided with evaluation and optimization components (Jiang and Nee, 2013).

In summary, new and innovative mathematical methods like metaheuristics pose several improvements and advantages over more simplistic methods from a scientific perspective. They are able to solve large problems quickly with solution qualities near the optimum and concurrently integrate several design aspects that have been solved in a sequential process so far. However, the software applications are still focusing on features that support the manual design process without the use of advanced algorithms. This gap motivates the investigation of the development procedures of software applications, the underlying intentions, used scientific methods and the assumed but unclear scientific impact on the procedures.

## 3 Research Methodology

As there is no comparable research so far, we used an approach of rather explorative nature. First, we conducted a market review to identify promising software applications for facility layout design that use scientific methods to arrange facilities in the manufacturing sites. Therefore, a systematic search was conducted using web databases, project descriptions and scientific articles. We then classified the identified software applications after a thorough review and analysis (see section 4).

Second, we conducted a multiple semi-structured interview study with experts from a subset of the identified software engineering companies. The semi-structured interview design allows flexibility to adapt to specific but initially unknown circumstances in practice (Yin, 2009). To analyze a representative sample of cases for the area of interest, the concept of theoretical sampling was used (Eisenhardt and Graebner, 2007). Therefore, four software engineering companies took part in the interview study. The cases develop and distribute software applications with implemented scientific methods, especially in factory design. Although the number of interviews is relatively small, in the limited field of facility design software solutions the selected cases and the findings are representative and can be theoretically generalized (Meredith, 1998). The organizational characteristics of the examined software companies are shown in Table 1.

Cases A, B and C represent software engineering companies of different size. Cases A and B are small companies operating in Germany with less than 15 employees. In contrast, case C constitutes a large company with headquarters in Germany and the USA and employing over 9,000 people. In order to investigate the layout design methods applied by a scientific organization, we also interviewed an institute of a university (case D). The interview partner of case D has developed a design software application and distributes it as a freelancer.

Table 1: Outline of the cases (Organization)

| Case | Employees | | Customers | | Contact with Science | Interviewee |
|---|---|---|---|---|---|---|
| | Number | Degree course | Sectors | Regions | | |
| A | 11 | ME/IE,CS | All | Worldwide | Software used in university courses | Managing Partner |
| B | 12-15 | ME/IE, | Automotive | Worldwide | Practice journals and associations (VDI) | Director |
| C | 9.000 | ME/IE,CS, E | All | Worldwide | University work-shops, confer-ences | Technical Specialist |
| D | 20 | ME/IE | All | Germany | Software used in university courses | Research Associate, Freelancer |

* ME/IE =mechanical / industrial engineering, CS = computer science, E = economics

Besides the distribution of software, all cases provide workshops and training courses to teach their customers as well as consulting services around layout design. The interviewed cases employ a highly skilled workforce with university degrees mainly in the fields of mechanical and industrial engineering. The customers of cases A to D operate in all sectors and industries around the world, though most are manufacturing companies. A comparison of project figures is complex since all cases stated that project durations and budgets differ depending on the specific customer needs. However, most projects range between a few days for basic training workshops to about three months for additional consultancy and may be extended by several months for major planning support.

Only case A actively cooperates with universities and scientific institutions regarding facility design projects. The interview partner of case B sporadically reads journals and uses the mutual exchange of information in associations like the Verein Deutscher Ingenieure (VDI) to stay up-to-date. There is no active collaboration considering the development of the software application with scientific institutions. This also applies for case C. Nevertheless, the interview partner takes part in workshops at universities and is a speaker at certain professional events. The academic institution of case D collaborates with colleagues from the same university in projects where they often utilize the software application. Further feedback comes from several other universities that use the software application for teaching and project purposes.

After the investigation of general characteristics, we applied an iterative approach for data collection, coding, and analysis (Eisenhardt, 1989). For preparation purposes and the appropriate selection of interview partners in the case companies, we provided the interview partners with a questionnaire prior to the interview as an extract from the guidance document. During the interview, we used the guidance document to focus on all relevant aspects. The data from the transcribed interviews was coded using MAXQDA 2018 to detect important aspects from the transcript.

All statements were grouped into categories referring to similar phenomena. According to a deductive-inductive approach, main categories were established prior to the interviews whereas subcategories were created from the investigation of the first transcript. In a first step, the text passages were grouped into the main categories. Organizational aspects like staff structure, company size, and customer features were grouped in ”Organization”. The second main category ”Software” covered aspects like application range and development procedures.

”Layout Planning” included the implemented scientific methods for facility design and all comments regarding advanced mathematical methods.

The ”Link to Science” was further analyzed in a fourth main category including the information approach towards current development and an assessment of the mutual exchange with scientific institutions. After the inductive determination of the subcategories, the whole document was grouped according to a differentiated system of categories (Kuckartz, 2014).

The analysis was carried out case-by-case first and completed with a comparative analysis. The resulting conceptual model represents a common understanding of phenomena regarding the cases. In addition to the interviews, we used company websites and provided material by the interview partners (brochures) to triangulate the interview data. The final reports were sent to the interview partners for validation purposes and to maintain participant engagement.

# 4 Findings

## 4.1 Market review on software applications

Table 2 illustrates the identified software applications and respective methods, features, and limitations. The software applications were then grouped into four categories and visualized in Figure 1. The two aspects of interest for this classification are the degree of integration of all planning tasks into the basic planning process of factory design (e.g. VDI, 2011) and the provided scope of functionalities for the arrangement of objects in the factory layout.

Table 2: Identified software applications and their respective scientific methods, features, and limitations

| Tool | Scientific method for facility design | Features | Limitations |
|---|---|---|---|
| AutoCAD | none | Widely used in the industry; enables a digital representation of possible real world systems | Only supports trial-and-error for facility arrangement without any quantified evaluation |
| G-MAFLAD | Branch-and-Bound (exact) | Considers facility dimensions for a first block layout variant | Users need to provide certain feasible arrangement sites for each facility; no material paths considered; limited import/export features |
| FACOPT | Simulated Annealing / Genetic Algorithm | Considers facility and factory (incl. gates) dimensions for a first block layout variant | Provides block layouts without considering material paths or real life requirements; not commercially available |
| VIP-PLANOPT | Simulated Annealing + Local Search | Considers facility dimensions; extensive configuration options (dimensions, shape flexibility, factory floor) | Considers predefined material paths via blocked areas in the layout; scientific method not fully disclosed |

| | | | |
|---|---|---|---|
| SIMOGGA | Genetic Algorithm | Considers various input data (factory floor, material paths, facility dimensions) | Only usable for cellular layouts with redundant resources; needs an initial solution to start upon |
| MALAGA | Greedy Heuristic | Integrated plant model; connection to simulation software (Plant Simulation by Siemens) | Facility dimensions neglected for first steps of factory design, dimensions need to be manually applied subsequently |
| Tecnomatix Factory Design | Graphical Method | Connection to various related software modules (Plant Simulation by Siemens) | Needs an initial solution to start with an optimization; no consideration of material paths and input/output points |
| SketchUp MF-VO | Graphical Method | Plugin for 3D software ”SketchUp”; presentation, analysis, and optimization of material flow; considers paths | Solution method provides recommendations for arrangement that need to be applied manually |
| visTABLE®touch | Greedy Heuristic | Combined tool for visualization and layout design; considers paths; quantified evaluation | Solution method provides recommendations for arrangement that need to be applied manually |

Although three identified applications used metaheuristics to arrange objects in the factory layout (VIP-PLANOPT, FACOPT and SIMOGGA), these applications are unable to connect with other commercial applications and therefore cannot be widely used. They only offer partial support for the factory design phases providing first block layout variants that need further fine-tuning, and were therefore entitled 'specific tools' in Figure 1. Comprehensive tools with a modern, user-friendly graphical user interfaces like visTABLE®touch or the SketchUp MF-VO Plugin still use simple but outdated methods, such as the method by Schmigalla (1968) or the method by Schwerdtfeger (Kettner et al., 1984).

## 4.2 Interview Study

Cases A, B, and D provide a single software application while case C provides several applications specified for different sectors. The mechanisms that led to the development of the software applications are similar in all cases. At the time of development, no product was available on the market which offered the functionalities that the interview partners needed for their projects. This led to in-house developments of software applications appropriate for the specified design projects after which cases A to D started offering their applications for sale to other engineering companies. The software was then increasingly enhanced in order to improve customer-orientation and user-friendliness. However, hardly any developments considering advanced scientific algorithms were adopted from contemporary scientific contributions. On the contrary, it is apparent that software developers are familiar with the general layout planning procedure of dividing the design task into several feasible smaller design steps (e.g. Schenk, 2014; Klausnitzer et al., 2017).

All cases use simple methods in their software applications to arrange objects in the sites. Case A uses greedy heuristics (related to the method by Schmigalla (1968) and the method by Martin (1976)) to optimize existing or initial layouts. Case B uses a modified approach of the method by Schmigalla (1968), while case C is currently testing an algorithm for a generative design of layout variants to generate a feasible layout variant. Case D uses the graphical method by Schwerdtfeger (Kettner et al., 1984) to arrange facilities. The interviewees are consistent in their skepticism towards the use of modern algorithmic approaches and stated that advanced algorithmic approaches are too difficult to apply in factory layout design. Moreover, the additional effort of implementing and applying the metaheuristics in comparison to simple heuristics does not represent a favorable

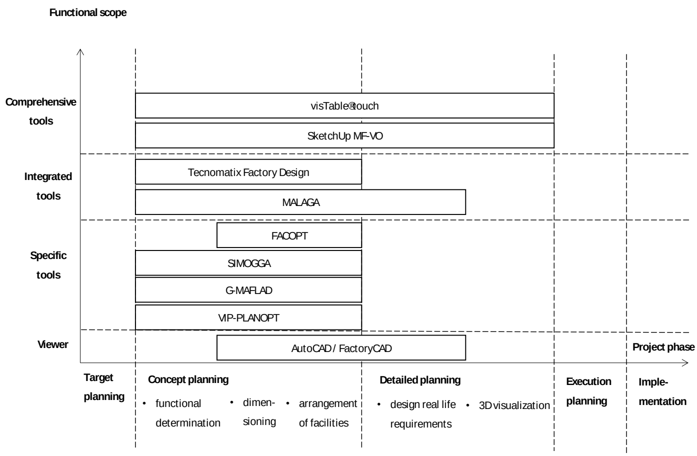


Figure 1: Classification of reviewed software applications for facility layout planning

cost-benefit ratio. Interviewees A and D further criticize that metaheuristics still only produce an initial solution for the layout problem. This solution has to be subsequently adjusted to real life requirements that were not considered by the algorithm.

The general skepticism about novel approaches suggests a lack of knowledge considering the existence of advanced algorithms. In all cases, the employees are usually mechanical and computer engineers. Advanced algorithms regarding the FLP as a long-time challenging discipline of operations research are usually not focused on these fields of study. Therefore, the interviewees are not aware of the considerable benefit in the quality of the layout solution and the potential of optimization of the overall planning. Since the traditional planning procedure suggests a top-down approach where restrictions are considered step by step, the planning process might run up against infeasible intermediate layout solutions several times that require multiple setbacks and replications of previous planning phases. In contrast, advanced computer supported layout design approaches can integrate several design elements and restrictions simultaneously within a single planning step. This leads to feasible layouts with respect to the considered restrictions and planning details. If such an algorithm is implemented within a software application, it is able to produce several layout variants within a few minutes that can be qualitatively and quantitatively evaluated and modified by the user. As discovered in this study, current software applications often only automate the relative arrangement of facilities using the approaches of Martin (1976) and Schmigalla (1968). Both approaches do not consider any restrictions, not even the areas of facilities and the planning areas. Therefore, solutions obtained with current applications frequently get stuck in infeasible intermediate solutions that require time-consuming replanning.

As regards the scientific education and the lack of implementability of advanced methods, interviewees A and C noted that the general quality of education has decreased and that it is difficult to find qualified employees capable of implementing advanced algorithms. This is enormously important for software developers like cases A to D since the software as well as the algorithms evolve continuously according to the design tasks. Moreover, interviewee B noted that there is a general lack of time to proactively enhance the software application. All interviewees are still occupied by the daily business of layout design projects due to their origins as software providers.

With regard to the customer's capabilities in factory design and planning, all interviewees are consistent in their observation that the majority of customers do not grasp the relevance of factory design. Particularly interviewees B and C noted that the customers are not aware of the overarching objective of minimizing the material handling effort in the layout design as a considerable contribution for long-term efficiency and success.

Instead, objectives like a resemblance to existing testimonial factory layouts or low alteration costs are prioritized, resulting in low layout performance and a redesign early on. In addition, only a few users of software applications use factory design methods correctly and consistently due to a lack of expertise and constant time pressure in the planning process. This difficulty could also be overcome by the use of advanced approaches in software applications for digital factory design. Interviewee A believes that with new Big Data analytics there is an opportunity to gain a deeper understanding of the impact of factory design methods on decision makers. Interviewee D foresees a shifting focus from simulation to Big

Data applications. The digital factory and the associated trend towards constant redesigns caused by the volatile markets, new technologies, and changing legal conditions must therefore trigger a rethinking of the users towards a consistent and transparent planning approach.

Moreover, interviewee B sees a nascent conflict between the planning department and the IT department. An adoption of advanced algorithms that integrate design aspects of several planning phases would result in major changes in the well-established planning procedure in all cases. Thus, the IT department is increasingly seizing more planning responsibility and decision-making power from the factory designers. Additionally, all interviewees hinted that layout designers want a transparent and comprehensive layout planning procedure. They are skeptical about layout solutions that are generated automatically by pushing a button. These statements can be summarized as general acceptance problems concerning advanced algorithms.

Despite the general wariness about advanced layout design approaches, particularly interviewees A and B showed strong interest in these methods and in a close cooperation with specialized scientific institutes. Especially interviewees A and C assume that metaheuristic solutions will play a greater role in future developments, which is closely related to the further increasing computing capacity.

# 5 Recommendations for Practice

As a result of the conducted study, it is clear that the software developers are currently not focusing on advanced algorithmic approaches. They are not aware of their existence, possible benefits and implementation and showed therefore a general suspicion. A closer collaboration with universities would pave a direct way for the implementation of promising methods and would facilitate superior software applications. Therefore, scientific institutions like universities have the task to change and modernize their factory design courses. They should enhance the strong engineering view with findings from operations research that has focused on the layout design problem for more than 60 years as a separate stream of research (Koopmans and Beckmann, 1957). Students need to be better prepared for the future challenges of factory design resulting from digitization. This includes training in software applications in support of the entire planning process. Additionally, the focus should shift from CAD systems to specialized factory design applications that consider the overall production planning process and the connected logistic processes.

Software providers often serve as consultants in layout design projects and therefore focus on employees with engineering skills. They should also consider employing specialists skilled in operations research to continuously develop the design software and to implement advanced approaches.

In order to solve the acceptance problems, interviewees A, B, and D noted that automated layout design solutions could be valuable if they are used for orientation purposes and in comparison to manually designed layout solutions. Hence, the customers' acceptance will increase and advanced scientific methods can be positioned and marketed as a key feature of the software application. Interviewee C states that a complete replacement of previous simple, greedy methods by metaheuristics is conceivable. Moreover, interviewee C noted that software solutions are generally acceptable if they are user-friendly without time-consuming training and difficult settings.

Interviewee B further recommends well-prepared key users for the usage of advanced solutions in software to ensure a correct use of the generated layouts. The key users should be guided through the design process while automatically focusing on the overarching aim to minimize the material handling effort. Simple and intuitive software usability as well as certain adjustment possibilities would further improve customer acceptance.

According to all interviewees, future software applications should support the entire design process. This also requires interface functions to export the solution into common data formats for further visualization and simulation. Interviewee D noted that integrating the algorithms into a three-dimensional planning procedure is of further importance. Since the interview partners were concerned about the decreasing influence of the users in case of implementing advanced algorithms in the software, literature suggests implementing expert systems (García-Hernandez et al., 2014). These advanced approaches allow for the consideration of the user's experience at several planning steps.

## 6 Conclusions

There are a significant number of publications in the scientific area of facility layout design, with an apparent trend towards metaheuristics and algorithm-based optimization of the arrangement problem. Although these advanced methods offer several advantages over traditional methods from a scientific perspective, our market review indicated that current design software still uses these simple and outdated methods in the applications. The prevailing part of the design task remains with the designer without any software support. This answers our first research question regarding the methodical support of factory design processes in software applications.

In order to investigate the reason for this practice-research gap and to identify future research direction, we further conducted a multiple interview study with experts from software engineering companies and a scientific institution that distributes a self-developed software.

As regards our second and third research question, our study showed that all investigated cases are connected to science to some extent and apply a similar general layout planning procedure that is well-known in manufacturing engineering research. Current advances in advanced algorithmic approaches from the scientific area of operations research are not affecting the interviewed software developers due to the fact that the case companies

— lack knowledge regarding the existence of advanced algorithms, caused by the scarcity of employees familiar with operations research;

— lack knowledge regarding the implementation, due to the decreased quality of the staff's education;

— lack knowledge regarding the usage of advanced algorithms, due to the use of the software by customers unskilled in layout design;

— expect problems of acceptance, since advanced algorithms that automatically solve design problems would shift reasonability and decision-making power from the designer to the IT department.

Even the scientific institute, with an anticipated deeper understanding of scientific advanced methods, still uses simple algorithms and reveals the same findings as the other cases. This suggests that the research communities (engineering and operations research) are segregated, although they focus on the same topic from different viewpoints.

This study further derived recommendations for practice in light of Industry 4.0, besides the motivation for an intensified cooperation of software developers and scientific institutes from different disciplines:

- software engineering companies should employ staff with specific operations research skills;
- the education of mechanical engineering in the field of manufacturing design should integrate specific operations research issues;
- advanced algorithms should be made user-friendly and be implemented as complementary features at first, until the customers have gained trust in these features.

## 7 Limitations and further Research

The results of this study are analytically generalizable in terms of correlative validity; however, there are some limitations. The validity of this interview study is within a clearly defined scope:

- Software manufacturers with branches in Germany, specialized in layout design software and services;
- Customers from the manufacturing industry (SMEs to multinationals);
- Individual consultation and fulfillment of customer requests within the projects.

Future research using a larger sample size with diverse industries and firm characteristics would improve reliability of this interview study. An approach which involves interviewing software manufacturers with an international focus should also be expedited in order to validate the findings.

Additionally, we indicate some recommendations for research in order to focus the research for a better applicability of findings in practice in the imminent trend to Smart Manufacturing and Industry 4.0:

The interview partners described several features that they expect from an advanced approach to be implemented in their software. Interviewees A and B demand real-time capabilities of the solution method to make use of the benefits of collaborative planning. Interviewees A and C consider several minutes as a time requirement for a sophisticated solution to be acceptable in terms of collaborative planning.

This allows for a discussion of often uncertain input data and the following solution evaluation in collaboration. Moreover, if the algorithm produces several layout variants, interviewee C expects a recommendation for a preferred layout variant. Interviewee D emphasizes the relevance of a comparison value with traditionally obtained solutions to classify the solution quality. Therefore, the software should be able to calculate the material handling effort expected from the obtained layout variant and should further enable the user to define customized evaluation criteria.

Besides the objective function aiming to minimize the material handling effort, several main restrictions were identified in the interview study that should be taken into account by researchers when developing a metaheuristic:

— Facility shapes

— Facility orientations

— Dimensions

— Path and aisle design

— Fixable functional areas

— Structural conditions, e.g. walls and pillars

Most scientific approaches already satisfy several of these requirements since they are often rather fast, evaluate an adjustable quantitative objective function value and satisfy most of the required restrictions. However, there are only a few approaches that consider three-dimensional layout information (Barbosa-Póvoa et al., 2002) and the material path system (Friedrich et al., 2018 ). To the best of our knowledge, there is still a lack of scientific approaches that explicitly consider the aisle design.

In order to make their findings better accessible for practitioners, scientific institutes should proactively support the comprehensibility throughout the research process. Researchers are moreover advised to publish their findings considering layout design in practice-relevant journals in addition to scientific journals.

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