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The single row layout problem with clearances

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To my family

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List of Abbreviations

FLP	Facility layout problem
NP	Non-polynomial
SA	Simulated annealing
SRELP	Single row equidistant layout problem
SRLP	Single row layout problem
VNS	Variable neighbourhood search

1 Introduction

1.1 Motivation

In today's volatile and competitive environment, companies face a multitude of challenges due to the ever-growing globalisation along with continously improving technologies and quickly changing market requirements (see, e.g., Ariafar / Ismail 2009, Lenin et al. 2013). Nowadays, customers demand products, that are tailored to their needs and desires, but which are often replaced within short intervals by newer variants (see Çil / Evren 1998). This trend is embodied by an increasingly customisation of products and higher product variety while product life cycles are shortened (see, e.g., Kouvelis / Kurawarwala / Gutierrez 1992, Benjaafar / Sheikhzadeh 2000, Lenin et al. 2013). Additionally, high fluctuations and difficult predictions of future product demand quantities (see Leung 1992b) and shorter delivery times (see, e.g., Benjaafar / Sheikhzadeh 2000, Singholi / Chhabra / Ali 2010) reinforce the challenges and complexity of modern manufacturing.

Therefore, coping with these cost and time pressures, manufacturers take advantage of new production concepts in use with advanced and flexible technologies (see, e.g., Ficko / Brezocnik / Balic 2004, Joseph / Sridharan 2011). This gives the ability to operate manufacturing systems which can rapidly and efficiently be adapted to these changed conditions while conventional requirements of producing with better quality and reliability, and at reasonable costs still have to be satisfied in order to sustain crucial competitive advantages (see Çil / Evren 1998, Singholi / Chhabra / Ali 2010).

The basis for such flexible, highly productive, and cost-efficient operations is an effective design of the manufacturing plant whereof especially the design of the physical layout of the system is one important issue to the success and long-term viability of any manufacturing company (see, e.g., Kusiak / Heragu 1987, Kouvelis / Chiang / Fitzsimmons 1992, Benjaafar / Sheikhzadeh 2000, Braglia / Zanoni / Zavanella 2003, Drira / Pierreval / Hajri-Gabouj 2007, Pillai / Hunagund / Krishnan 2011, Hosseini Nasab et al. 2018). A well-designed facility significantly affects the overall performance and productivity of the production system since it contributes to the enhancement of product quality, reduction of manufacturing costs and lead times and, hence, to the increase of throughput of the system (see El-Baz 2004, Ficko / Brezocnik / Balic 2004, Nearchou 2006, Ioannou 2007, Pourvaziri / Pierreval 2017, Hosseini Nasab et al. 2018). In return, an inefficient layout may result in increased work-in-process, longer transportation times and disordered material handling with higher material handling costs (see Leung 1992a, Ioannou / Minis 1998, Pillai / Hunagund / Krishnan 2011) as well as inproper utilisation of available floor space (see Ahmadi / Pishvaee / Jokar 2017). Furthermore, a facility layout is a long-term and costly investment, so that subsequent changes in the machine locations are usually not possible or require high expenditures (see Chiang / Chiang 1998, Murthy et al. 2016).

The corresponding optimisation problem is known as the *facility layout problem (FLP)* and is generally concerned with the optimal arrangement of machines, machinery tools and equipment in the plant area subject to different constraints so as to achieve the desired production results (see, e.g., Drira / Pierreval / Hajri-Gabouj 2007, Ariafar / Ismail 2009, Klausnitzer / Lasch 2016, Friedrich / Klausnitzer / Lasch 2018). Since the efficiency of facility layouts can be measured in terms of cost, the most common objective of the facility layout problem is the minimisation of material handling cost incurred by transporting material from one machine to the next one (see Meller / Gau 1996). The material handling cost usually depends on the frequency of material movement and the distance which has to be covered between any two machines (see Ahmadi / Pishvaee / Jokar 2017, Tuzkaya et al. 2013).

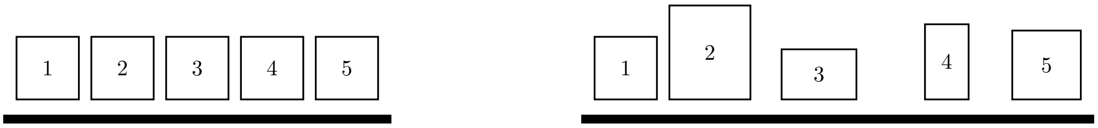
With regard to various manufacturing characteristics and constraints, a vast amount of optimisation problems related to different aspects of the facility layout problem has been considered in the research literature during recent decades. Among them, one special variant of FLP frequently adopted in modern manufacturing systems is the well-known *single row layout problem (SRLP)* which is the topic of this thesis. In particular, within this work, we intend to analyse the impact of incorporating clearances among machine pairs into the SRLP for the purpose of meeting the practical needs of today´s manufacturing more appropriately. For this, different types of clearances are examined and proper modifications to the basic SRLP model as well as novel heuristic solution approaches are provided to handle the problem's extensions.

1.2 Fundamentals of SRLP

The single row layout problem consists of finding the most efficient arrangement of a given number of rectangular machines placed along one side of the material transportation path with the purpose of minimising the total weighted sum of distances among all machine pairs. The total weighted sum of distances is thereby composed of the pairwise material flow and the corresponding centre-to-centre distance of any machine pair (see, e.g., Tubaileh / Siam 2017). The objective value is high if either the handled material flow between machine pairs is high or the machines are arranged far away from each other. Commonly, both the material flow as well as the lengths of machines are assumed to be known. Since machines are placed along their lengths and therefore the machine's width is not directly connected with the assignment, this problem is also known as the one-dimensional space allocation problem in literature (see, e.g., Picard / Queyranne 1981, Anjos / Vieira 2017) and was first introduced by Simmons in 1969.

The simplest version of SRLP is the single row equidistant layout problem (SRELP) that is a special case of the quadratic assignment problem where a given number of machines is assigned to the same number of locations (see Figure 1.1(a)). Here, in SRELP, it is assumed that all potential locations for each machine in the single row are known in advance with predefined, equal-sized distances (see, e.g., Hungerländer 2014, Palubeckis 2015b). From this, it is implicated that all machines are identical in size and shape, typically rectangular or squared, according to the predetermined locations. Therefore, distances between locations, and hence between machines, do not change due to different machine sequences (see Solimanpur / Vrat / Shankar 2005).

However, in most real-life manufacturing environments, this is not an appropriate assumption since machines performing different operations usually are of unequal sizes (see Solimanpur / Vrat / Shankar 2005). In many SRLP research papers, this limitation is overcome by considering machines of varying length. As a consequence, the distances between machine pairs differ and then depend on the respective sequence of machines arranged in the single row (see, e.g., Ozcelik 2012).



(a) Single row equidistant layout problem. **(b)** Single row layout problem with clearances.

Figure 1.1: Single row layout with material transportation path.

Extended and further practical problem settings additionally include equal or unequal clearances in which, e. g. different storage zones, corridors for operators or areas for maintenance depending on its neighbouring machines are considered (see Figure 1.1(b)).

The SRLP belongs to the class of combinatorial optimisation problems whose solution space Π is composed of permutations $\pi \in \Pi$ on a set of elements N; machines in this regard (see, e.g., Palubeckis 2015a, Palubeckis 2017). Thus, in the case of SRLP, the objective is to find a permutation $\pi = (\pi_1, \dots, \pi_n)$ of n machines in $N = \{1, \dots, n\}$ that minimise the total costs.

The optimisation problem can mathematically be formulated as

$$\min_{\pi \in \Pi} \sum_{\substack{i,j \in N \\ i<j}} f_{\pi_i \pi_j} \, d_{ij}^{\pi}, \tag{1.1}$$

s. t.

$$d_{ij}^{\pi} = \frac{l_{\pi_i}}{2} + \sum_{k=i}^{j-1} e_{\pi_k \pi_{k+1}} + \sum_{k=i+1}^{j-1} l_{\pi_k} + \frac{l_{\pi_j}}{2} \, . \tag{1.2}$$

Characterised by its given length l_{π_i}, each machine π_i is connected to other machines by the associated material flow $f_{\pi_i \pi_j}$, where π_i and π_j represent the machines at the ith and jth position in π respectively. The distance between the centroids of any two machines π_i and π_j is denoted by d_{ij}^{π}, $i < j$, in the particular permutation $\pi \in \Pi$. Additionally, with regard to the main attention of this thesis, the SRLP comprises clearances between machine pairs (π_i, π_j) denoted by $e_{\pi_i \pi_j}$. To represent all necessary components, in Figure 1.2 the determination of distance d_{15} between two machines $\pi_1 = 3$ and $\pi_5 = 4$ at position 1 and 5 respectively in an arbitrary selected permutation $\pi = \{3, 5, 1, 2, 4\}$ is exemplified.

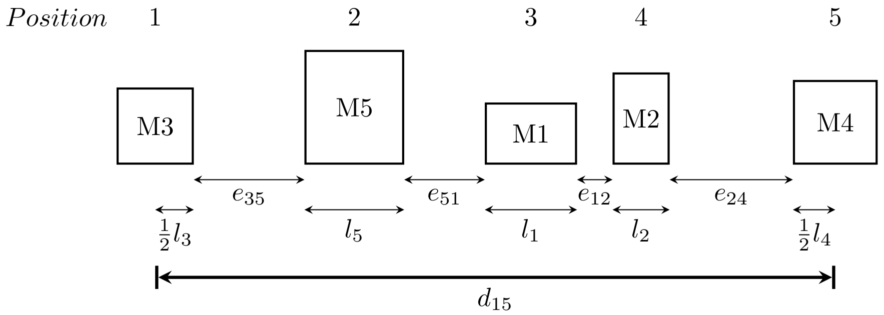


Figure 1.2: Exemplified determination of distance d_{15} for arbitrary permutation $\pi = \{3, 5, 1, 2, 4\}$.

Altogether, common characteristics of the SRLP considered in this thesis are:

- Machines are of varying dimensions, but all are considered to be rectangular.
- Distances between machines are measured with respect to their centroids.
- The material flows (connectivities) between machines are known as well as the machine's dimensions (length).
- Clearances required between each pair of machines are variable. Different machine pairs require different clearance sizes so that clearances depends on the machine sequence in the single row.
- Orientation of machines is predetermined in respect of the transportation path.

The SRLP has a variety of applications reported in literature. Most of the works are motivated by arranging machines in manufacturing systems, both flexible (see, e.g., HERAGU / KUSIAK 1988, KOUVELIS / CHIANG 1992) and cellular (see, e.g., YU / SARKER 2003). Apart from this, it has been used to model the optimal arrangement of rooms along one side of the corridor in hospitals as well as departments in office buildings and supermarkets (see SIMMONS 1969). Assuming facilities with equal lengths in the SRLP, common applications are the assignment of airplanes to gates in an airport terminal (see SURYANARAYANAN / GOLDEN / WANG 1991), optimisation in sheet-metal fabrication (see ANEKE / CARRIE 1986), minimisation of wire length in VLSI design (Very Large Scale Integration) (see CHENG 1987) and arrangement of circuit components in electronic systems with minimal wire length (see BHASKER / SAHNI 1987, CHENG 1987). Furthermore, the same problem occurs in design of warehouse layouts so as to considerably reduce the time for retrieving or stocking products in warehouse shelves (see PICARD / QUEYRANNE 1981).

Besides its practical relevance, the special layout configuration of single rows has enjoyed lasting interest for almost 50 years since its introduction by SIMMONS (1969) and as more than 170 papers published to date are related to this field of research.[1]

In most of them, authors discuss and develop various solution methods, both exact and heuristic. Due to the $\mathcal{NP}$-hardness and the associated high degree of complexity of the problem (see PALUBECKIS 2015b), only instances with up to 40 machines are solved to optimality, since exact approaches for the SRLP require high computational effort and time. Thus, to generate single row layouts consisting of a large number of machines, researchers focus on heuristic optimisation procedures to obtain reasonable good solutions in acceptable computational time. The existing studies can be broadly

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[1] As described in KELLER / BUSCHER (2015), more than 145 publications related to SRLP were found during our research. In the years after our survey has been submitted, this amount is increased by almost 30 papers.

categorised into construction heuristics and improvement approaches. The former type uses certain problem features and structures of the SRLP to quickly and easily yield a feasible solution. However, the solution quality is typically lower than that obtained by improving heuristic approaches (see Blum / Roli 2003). Improvement methods are known as meta-heuristics in literature. Being a general algorithmic framework, they can be applied to a wide range of problem types, but have to be tailored to the specific problem in order to be efficient. Meta-heuristics iteratively exploit the search space starting from one or more initial feasible solution. By accepting even worse solutions, they beneficially enable to overcome local optima.

Good summaries of solution approaches covering (parts of) the research area of this thesis are available in Kothari / Ghosh (2012), Hungerländer / Rendl (2013), Keller / Buscher (2015) and Anjos / Vieira (2017) as well as Hosseini Nasab et al. (2018) for the FLP in general. Some recently published studies not described therein comprise well-established meta-heuristics such as simulated annealing, tabu search and genetic algorithms as well as modifications and extensions based on them. The works of Palubeckis and Guan / Lin are the most notable ones which provide very efficient algorithms by analysing and utilising specific properties of the single row layout. For large size SRLP instances with up to 300 machines, Palubeckis (2015a) introduced a variable neighbourhood search (VNS) meta-heuristic that incorporates different local search procedures. These algorithms are able to explore the neighbourhoods considered (insertion-based and pairwise interchange) in a fast and efficient manner. The authors explicitely considered clearances of variable size so as to fulfil real-life requirements. To find high-quality solutions for the equidistant case of SRLP, Palubeckis (2015b) proposed a multi-start simulated annealing (SA) algorithm where at each iteration two possible neighbourhoods (pairwise interchange or insertion) are selected depending on random number. Additionally, the authors implemented a speed-up technique to efficiently calculate the difference of objective values between current and candidate layout (gain). For higher temperatures, only one neighbouring solution is considered, whereas for lower temperatures the best of all possible neighbours is selected. This approach was extended by Palubeckis (2017) to generate single row layouts with clearances between adjacent machines. In that work, problem instances with 1000 machines were evaluated. Another outstanding meta-heuristics was developed by Guan / Lin (2016b) who combined VNS with ant colony optimisation for finding an efficient arrangement of machines in a single row. The VNS component is responsible to intensify the search process within a promising area of solution space, whereas the ant colony algorithm is used for diversification of the search. Three kinds of neighbourhood structures were applied: insertion, interchange and swap movement. As stated by the author, this algorithm is superior to state-of-the-art meta-heuristics with regard to both, solution quality and computational effort. Guan / Lin (2016a) introduced a multi-start local search approach to solve large size instances of the SRLP. A first-improvement procedure is employed in the insertion neighbourhood where a speed-up technique reduce the computation time to obtain the cost of neighbouring solutions.

A practical extension to the basic SLRP was considered by Yu / Zuo / Murray (2014). The authors suggested a new type of clearances which may be shared by both adjacent machines. This type of SRLP was solved by tabu search. Srinivas et al. (2014) discussed the application of sensitivity analysis used to determine the parameters of genetic algorithm for the SRLP. They intended to establish a guideline to find the most favorable parameters. While most of the previous works to date for the SRLP are based on minimising the sum of distances between machines, Tubaileh (2014) proposed a SA based procedure in which the kinematic characteristics of the material handling device is incorporated by considering its velocity and acceleration as design parameters. Machines are therefore arranged in such a way that the total traveling time required to move the materials or products from one machine to the next one is optimised. In Hosseini Nasab / Kamali (2015), the problem was tackled by another SA algorithm that use an initial solution obtained from one of four construction heuristics developed by the author. These heuristics construct a feasible single row layout based on different principles: randomly, cost-based, machine length based and a variant combining the latter two ideas. Tubaileh / Siam (2017) introduced a SA and an ant colony optimisation algorithm to solve the SRLP where the clearances required between machines is included in the machines' dimension. To address the SRLP in automated manufacturing systems, Murthy et al. (2016) hybridised SA and two flow line analysis methods for bidirectional and unidirectional material flow paths, respectively. The objective of the problem considered is to maximise the number of in-sequence movements. Incorporating sequence-dependent clearances in the context of placing machines along a single row, solution approaches based on particle swarm optimisation, genetic algorithm and artificial immune system was addressed by Saravanan / Kumar / Rajkumar (2016). In Rubio-Sánchez et al. (2016), the authors described an hybridised procedure which is based on the combination of the GRASP approach with a path relinking algorithm to determine a single row layout. This approach is able to obtain the best known solutions from literature and better solutions for one instance previously reported. Yeh et al. (2017) used the simplified swarm optimisation technique with an integrated local search procedure based on Samarghandi / Taabayan / Jahantigh (2010) for solving SRLPs with clearances fast and efficiently. Lenin et al. (2018) treated the SRLP as a bi-objective optimisation problem by reducing total flow distance of products and total length of the flow line at the same time. An efficient single row layout is generated by an artificial bee colony algorithm. Kalita / Datta (2018) questioned the assumption in SRLPs of an unrestricted placements of machines in the single row layout by adding positioning and ordering constraints. The resulting constrained SRLP is modelled and solved by a modified genetic algorithm considering the specific requirements.

Apart from this, non-traditional optimisiation techniques were discussed by several authors who transfered concepts adopted from various natural systems. For instance, by simulating the social behaviour of animals, Büyüksaatçi (2015) first introduced a bat algorithm that idealised the echolocation of bats guiding them in flying and for finding their preys. Maadi / Javidnia / Ghasemi (2016) proposed a cuckoo and forest optimisation approach. The former aims to find the best environment (solution) for breeding and reproduction of cuckoos. In the latter, trees represent a solution to the SRLP and the procedure attemps to find the most robust (best) tree in its suitable habitat. Gopal / Gandhimathinathan / Arunajadeswar (2015) and Kumar / Kumar (2016) applied an artificial immune system algorithm to the SRLP where the total material handling costs arising through the material movement between machines are minimised. In both papers, clearances of equal and unequal sizes are considered. Adopted from physics, Kaveh / Safari (2014) established a new optimisation method by applying a charged system search algorithm in which each solution is considered as a charged particle with a fitness value representing its magnitude of charge. An alternative approach was provided by Ning / Li (2017) who implemented the exhaustive insertion-based local search proposed by Palubeckis (2015b) within a cross entropy based algorithm. Their approach takes advantage of the symmetry characteristic of the basic SRLP without clearances.

1.3 Scope of thesis and research questions

Even though machines are positioned as close as possible to each other due to the optimisation objective of the single row layout problem, a minimum space between adjacent machines may be required to reflect real manufacturing situations by observing technological constraints, safety considerations and regulations. Preventing machines to touch each other, appropriate clearances ensure a safe and efficient performance of regular machine operations. For example, machines process a variety of different jobs and production steps with different production rates and makespans which cause the need to store products or components temporarily before the next process can be executed or the material handling device will transport them to the next machine (see Solimanpur / Vrat / Shankar 2005, Yu / Zuo / Murray 2014). Furthermore, clearances are required to load and unload machines (see Das 1993) as well as to allow workers and technicians unobstructed access to machines while operating them or carrying out maintenance and repairs such as opening control and instrument panels as well as exchanging damaged machine components (see, e.g., Kaku / Rachamadugu 1992, Chung / Tanchoco 2010, Brunese / Tanchoco 2013, Zuo / Murray / Smith 2016). Likewise, there must be enough space between machines to guarantee a fast evacuation in case of emergency (cf. Xie / Sahinidis 2008). In the presence of hazardous and sensitive utilities, materials or operations, corresponding machines may need to be separated far away from each other in order to avoid interferences (see Heragu / Gupta 1994 and Yu / Zuo / Murray 2014). In addition, vibrations, emissions of oscillation or the requirements of ventilation must be taken into account by sufficient space between machines.

Consequently, the type and size of the minimal separation between machines varies considerably according to the production settings as well as which machines are assigned side by side in the machine layout. For an appropriate representation of these different manufacturing conditions, different SRLP formulations with regard to clearances are required. Hence, this thesis intends to outline the different concepts of clearances that are used in literature and to categorise them so as to provide a profound understanding of the problem considered and to evaluate the effects on modelling and solution approaches for the SRLP.

A first decisive step is therefore a thorough and systematic review of researches related to the topic of SRLP in manufacturing systems in general and to the specific characteristics and requirements of clearances in particular. With this, not only the state of knowledge and research is presented, but also gaps in literature so far are observed which merit further investigations. In addition, an appropriate basis to meet the requirements of our research are revealed.

One of the first publications discussing the issue of clearances in more detail is the work of Solimanpur / Vrat / Shankar (2005), who emphasise the importance of clearances of different sizes between machine pairs in the context of SRLP. Depending on the manufacturing requirements, the clearance is sequence-dependent and influenced by the machines placed adjacent to each other in the single row. In this case, the single row layout is symmetric so as the left and right ends can be exchanged without increasing or decreasing the distance values and, thus, the objective value (see, e.g., Anjos / Kennings / Vannelli 2005, Anjos / Vieira 2017). This observation widely used is not longer valid if an arrangement of machines in a single row include not only unequal, but also asymmetric clearances. This enhanced problem consider a minimum space between any two machines depending on which machine is assigned before or after the other one. That means the distances between machines in a permutation $\pi = (\pi_1, \ldots, \pi_n)$ may not equal the distances of its reverse counterpart $\pi' = (\pi_n, \ldots, \pi_1)$. However, as described above, other production environments enforce additionally large separations between machines. Therefore, we further extend the types of clearances known in literature in order to approximate more real-life manufacturing conditions. All these variations of the basic SRLP represent a more complex problem as it comprises the determination of both the relative order of machines in the layout and their exact positions related to each other. Therefore, a major scope of this thesis is to provide novel solution approaches which explicitely integrate the problem specific characteristics of different types of clearances.

In accordance with this, the scope of this thesis can be summarised in the following research questions:

Q1: What is the current state of research for single row layout problems and what are the gaps in the research literature? What types of clearances can be differentiated in the relevant SRLP literature?

Q2: How does the integration of asymmetric, sequence-dependent clearances affect efficient construction heuristics for the SRLP?

Q3: How can well-proven meta-heuristics be adapted for the SRLP with asymmetric, sequence-dependent clearances to obtain good quality solutions?

Q4: What effect does the integration of asymmetric, sequence-dependent and machine-spanning clearances have on the modeling of an appropriate SRLP?

Q5: Does considering machine-spanning clearances require adjusted heuristic approaches for generating feasible solutions within computationally reasonable time?

1.4 Structure of work

To discuss the research questions derived, the thesis is divided in six chapters which summarises the research problems pursued and outlines their relations as depicted in Figure 1.3. Each of these chapters refer to one publication by the author whereof special aspects of SRLP with sequence-dependent clearances are adressed.

First of all, in **Chapter 2**, an extensive analysis of literature published in the research area of SRLP since 2000 forms the basis for further researches in the following chapters.[2] After a short introduction to the topic, the SRLP is positioned in the hierarchy of facility layout problems. Each of the 82 articles surveyed were classified with regard to the general

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[2] Chapter based on KELLER / BUSCHER (2014): *Single row layout models.*

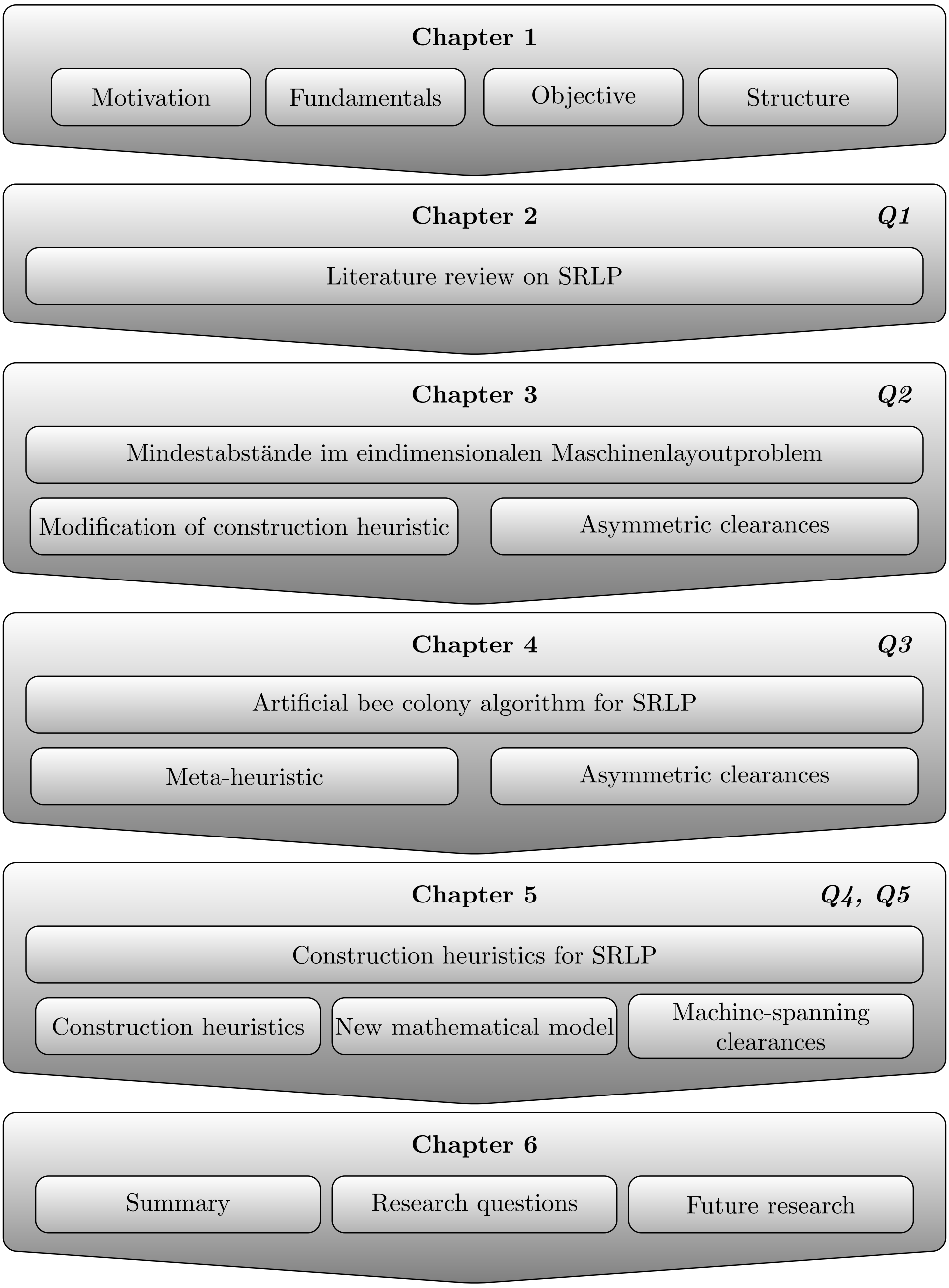

Figure 1.3: Structure of this thesis.

characteristics such as topic of the paper, model formulation and representation, type of input data, objective function, and solution methods. Particular attention is given to both model formulations and solution approaches in detail in order to adress the variety of objectives and constraints found in SRLP literature. In the former category, papers divided by discrete and continuous representation are discussed which is supplemented by recent developments considering extensions and special characteristics such as sequence-dependent clearances. The latter comprises exact approaches, heuristics, meta-heuristics and solution approaches based on simulation or knowledge-based expert-systems. Finally, by summarising the review, we elaborate some possible directions and opportunities for further research. This will give an comprehensive disscussion of ***research question Q1***.

As confirmed in the literature analysis, clearances are one important modification to the basic single row layout model, but are either insignificantly incorporated or ignored altogether, contrary to their high relevance in practical manufacturing systems.

To the best of our knowledge, the model of SOLIMANPUR / VRAT / SHANKAR (2005) is the only one which can handle both sequence-dependent as well as asymmetric clearances and, therefore, forms the basis for further considerations in this thesis and, in turn, for all subsequent chapters and ***research questions Q2 to Q5***.

Chapter 3 is an initial approach to this topic by presenting a modified construction heuristic for the SRLP with asymmetric, sequence-dependent clearances which is based on an efficient algorithm proposed by DJELLAB / GOURGAND (2001).[3] In the procedure, the structure of the current solution is exploited and machines are iteratively inserted at the best position in the partial layout using a priority order. The determination of the distances between adjacent machines have to be modified to suit the characteristics of asymmetric clearances. The influence of this problem specific modification is exemplified by comparing it to the common constructive heuristics for the SRLP obtained from literature. This will give an detailed answer to ***research question Q2***.

While in the previous chapter, the construction of an initial single row layout was focused on, the next logical step will be to obtain a (near) optimal solution for the SRLP by an improvement heuristic. Thus, in **Chapter 4**, we propose an artificial bee colony algorithm (ABC) to adress the SRLP.[4] Although the ABC meta-heuristic was first published in 2005 by KARABOGA, it has enjoyed major attention since then in a wide range of applications due to its competitive results compared to other heuristical solution approaches (see KARABOGA / GORKEMLI 2011). Nevertheless, it has not been attempted to the SRLP so far. Like other swarm-based heuristics, the ABC algorithm simulates the natural behaviour of organisms living in swarms to cooperatively achieve complex tasks (BLUM / LI 2008). In the case of ABC, the intelligent foraging behavior of honey bees is mimicked. Since it is developed for numerical optimisation problems (KARABOGA 2005), this population-based meta-heuristic must be adapted to the characteristics of SRLP. Mainly, modifications are discussed regarding the evaluation of the profitability of food sources, which represent the objective value of each solution, as well as the search mechanism to discover new food sources. With the purpose of reducing the computational complexity and for comparison

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[3] Chapter based on MAYER / BUSCHER (2012): *Einbeziehung von Mindestabständen in die eindimensionale Maschinenlayoutplanung.*

[4] Chapter based on MANZKE / KELLER / BUSCHER (2018): *An artificial bee colony algorithm to solve the single row layout problem with clearances.*

reasons, the originally phases of the algorithm were rearranged as suggested by Mernik et al. (2015). However, the performance of the modified version with respect to the control parameters (*SN, Limit, MCN*) was evaluated by conducting exhaustive preliminary tests. In order to investigate computationally the applicability of the ABC algorithm to the SRLP with clearances, new instances for the case of asymmetric, sequence-dependent clearances are generated and thorough analysis are conducted based on them as well as on well-known benchmark instances from literature without asymmetric clearances. This chapter belongs to ***research question Q3***.

As described earlier in this thesis, clearances are necessary so that regular machine operations can be performed safely and undisturbed. Depending on the manufacturing environment, the type of operations and/or raw material and utilities in use, it may not be sufficient to incorporate a required space only among adjacent machines. Instead, also the minimal required clearance between machine pairs placed further away from each other must be met, even if there are machines inbetween. For instance, this case needs to be adressed when machines emit oscillations or other undesired interactions over a large distance and would influence other machines with highly sensitive components. Hence, in **Chapter 5** and with regard to ***research questions Q4 and Q5***, we introduce an extension to the SRLP considered so far where this new kind of clearances reflects the reality in modern flexible manufacturing environments more appropriately.[5] In doing so, this paper is the first approach in literature that consider single row layouts including so-called machine-spanning clearances. Thus, a profound discussion of distinguishing properties arising from the integration of this type of clearances is conducted. Thereafter, the new mathematical model for the SRLP with machine-spanning clearances is established with aim of minimising the weighted sum of distances. To generate an initial solution, three different construction heuristics were developed incorporating machine-spanning clearances explicitely. In addition, the computational evaluation of the proposed solution approaches are presented and supplemented by comparisons to the best known construction heuristics from literature.

Finally, in **Chapter 6**, we summarise our work and draw conclusions by discussing our research questions stated at the beginning in Section 1.3. Based on this, some interesting future research directions regarding the SRLP in general and with sequence-dependent clearances in particular are provided.

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[5] Chapter based on Keller (2019): *Construction heuristics for the single row layout problem with machine-spanning clearances.*

2 Single row layout models (reference only)

Reference

Title	*Single row layout models*	
Authors	BIRGIT KELLER (BK), UDO BUSCHER (UB)	
Published in	European Journal of Operational Research, vol. 245, no. 3, 2015, pp. 629 – 644	
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Contribution to the publication[a]	Establishing of research topic	BK, UB
	Literature review	BK
	Conducting of research	BK
	Appraisal and interpretation of results	BK
	Publication strategy	BK
	Writing of manuscript	BK
	Pre-review and lectorship	BK, UB

[a] Underlined initials, if any, indicate authors with a major share in the respective field.

3 Einbeziehung von Mindestabständen in das eindimensionale Maschinenlayoutproblem (reference only)

Reference

Title	*Einbeziehung von Mindestabständen in das eindimensionale Maschinenlayoutproblem*	
Authors	Birgit Mayer (BK), Udo Buscher (UB)	
Published in	Innovative Produktionswirtschaft. 2012, Ed. by C. Mieke/ D. Braunisch. Berlin: Logos Verlag, pp. 131 – 149	
Contribution to the publication[a]	Establishing of research topic	BK
	Literature review	BK
	Conducting of research	BK
	Appraisal and interpretation of results	BK
	Publication strategy	BK, UB
	Writing of manuscript	BK
	Pre-review and lectorship	BK, UB

[a] Underlined initials, if any, indicate authors with a major share in the respective field.

4 An artificial bee colony algorithm to solve the single row layout problem with clearances (reference only)

Reference

Title	*An artificial bee colony algorithm to solve the single row layout problem with clearances*	
Authors	Laura Manzke (LM), Birgit Keller (BK), Udo Buscher (UB)	
Published in	Information Systems Architecture and Technology: Proceedings of 38th International Conference on Information Systems Architecture and Technology – ISAT 2017. Ed. by Z. Wilimowska/ L. Borzemski/ J. Świątek. *Advances in Intelligent Systems and Computing.* Springer International Publishing, vol. 657, pp. 285 – 294	
Link	https://doi.org/10.1007/978-3-319-67223-6_27	
Contribution to the publication[a]	Establishing of research topic	LM
	Literature review	LM, BK
	Conducting of research	LM, BK
	Appraisal and interpretation of results	LM, BK
	Publication strategy	BK, UB
	Writing of manuscript	BK, UB
	Pre-review and lectorship	BK

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[a] Underlined initials, if any, indicate authors with a major share in the respective field.

5 Construction heuristics for the single row layout problem with machine-spanning clearances (reference only)

Reference

Title	*Construction heuristics for the single row layout problem with machine-spanning clearances*	
Authors	Birgit Keller (BK)	
Published in	INFOR: Information Systems and Operational Research, vol. 57, no. 1, 2019, Facility Layout Part II, pp. 32 – 55	
Link	https://doi.org/10.1080/03155986.2017.1393729	
Contribution to the publication	Establishing of research topic	BK
	Literature review	BK
	Conducting of research	BK
	Appraisal and interpretation of results	BK
	Publication strategy	BK
	Writing of manuscript	BK
	Pre-review and lectorship	BK

6 Conclusion and future research opportunities

In this thesis, we studied the single row layout problem, a specially structured instance of the classical facility layout problem. In general, an efficient arrangement of machines within a manufacturing plant is a crucial issue to a company´s success and to maintain competitiveness for it contributes beneficially to the overall performance of the manufacturing system by decreasing material handling costs and lead times as well as increasing productivity.

The SRLP is defined as the placement of a given set of machines along one side of the transportation path so as to minimise the weighted sum of distances among all pairs of machines. With their simple, clearly structured and efficient configuration, single row layouts can be more easily designed, controlled and maintained explaining the popularity in practice. Besides this, the problem also aroused considerable interest in operations research literature from a mathematical point of view due to its combinatorial complexity.

To deal with the steadily growing amount of SRLP literature, we presented a comprehensive survey of articles published in this research area since 2000. By identifying recent developments and emerging trends, this overview shall help to understand the current research progress of this special kind of facility layout problem and may form a basis for further researches. In contrast to previous overviews focusing only on particular aspects of single row layouts such as model formulations or solution techniques, our review conducted is more extensive by providing a detailed analysis and classification of SRLPs with respect to model formulation, objective function in use, solution approaches as well as extensions and modifications of the basic layout problem. Special attention was given to problem specific aspects of SRLP in modern flexible manufacturing environments. In particular, clearances were considered, which are the necessary space between machines to ensure regular machine operations. According to the conclusions obtained in our review, we extended the common SRLP by assuming different types of clearances in order to meet the conditions of practical facility layout problems. Though, considering clearances necessitated the development of novel solution approaches, both exact and heuristic procedures. Therefore, for single row layouts separated by asymmetric, sequence-dependent clearances, a constructive as well as an improving meta-heuristic based on a nature inspired concept have been suggested. Furthermore, we consider manufacturing situations where large sized clearances between non-adjacent machines are needed for a safe environment. The relevance and applications of this new problem have been indicated and several construction heuristics were developed incorporating the particular characteristics of machine-spanning clearances which distinguish significantly this problem from classical SRLP without minimum required spaces among machines.

To answer the research questions aroused in the beginning of our thesis, the following results of each individual publication are merged.

Considering ***research question Q1***[1], our survey in Chapter 2 revealed that SRLP has been studied extensively in the literature in the past years. Whereof the focus of researchers is mainly placed on effective models and fast but also high-quality solution methods for the continuous SRLP. Owing to the computational complexity of this $\mathcal{NP}$-hard combinatorial optimisation problem, only instances with up to 40 machines have been solved by exact approaches. Although novel mixed-integer programming and semidefinite programming formulations further new directions of research and are very promising to obtain optimal single row layouts. Thus, particular attention is paid on improving and developing approximate solution methods, especially meta-heuristics, to adress the variety of objectives and constraints in SRLP formulations. State-of-the-art meta-heuristics, such as genetic or hybridised scatter search algorithms, are capable of arranging single rows with more than 100 machines in a reasonable amount of computational time for commonly used benchmark instances by explorating efficiently a predefined search space. In recent years, new approaches imitating the behavioural nature of organisms or transfering biological concepts have successfully been applied to the SRLP. Whereas construction heuristics are almost neglected by researchers in the period considered since only a limited number of papers propose approaches generating iteratively at least one initial feasible solution.

Within this review and in turn in the present thesis, the main focus is particularly and extensively paid on clearances as one of the extensions of the basic SRLP which profoundly influence model formulations and solution techniques.

Interestingly, despite the numerous examples for the practical importance, the relevance of clearances is treated inconsistently in the SRLP literature entailing different strategies and types of clearances. There are three main broad classifications of clearances. First, many authors assume that the required clearances between any machine pair are all

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[1] What is the current state of research for single row layout problems and what are the gaps in the research literature? What types of clearances can be differentiated in the relevant SRLP literature?

equal to a constant value. In this case, the length of each machine can appropriately be adjusted in such a way that the problem can be treated as a SRLP without clearances. Hence, the SRLP is simplified. The counterpart to these kind of clearance are those with different sizes that are dependent on the respective machine sequence in the single row. Divided in symmetric and asymmetric, sequence-dependent clearances applied to SRLP reflect indispensable requirements of real-life manufacturing environments. The majority of studies considering clearances cover the former case, whereas the latter is almost neglected to date in the corresponding literature. Thus, in accordance with the results of our literature survey and to close the gap in research, all following Chapters 3 to 5 focused on asymmetric and sequence-dependent clearances to be integrated in the SRLP in particular. This assumption builds the theoretical framework of the thesis. Whereat, each chapter discusses a new, but distinct aspect of clearances in the context of single row layouts based on the problem considered in the previous chapter.

With regard to ***research question Q2***[2], the symmetric characteristic of the single row layout as a widely common assumption in the respective research literature was lifted in Chapter 3 and the resulting impact on a fast, but still efficient solution approach for the SRLP was analysed. For this, a variation of the Best-Insertion heuristic proposed by DJELLAB / GOURGAND was developed incorporating the more complex case of asymmetric clearances. This requires an adjustment of the distance determination whereof the order of machine pairs in the permutation has to be explicity taken into account. This efficient construction heuristic was chosen since its solutions either match the best-known solutions for the common SRLP or surpass most of the other methods mentioned in the literature. Due to the limited number of instances investigated, no general statement concerning the quality of the provided heuristic can be formulated. Nevertheless, compared to other state-of-the art construction heuristics, a detailed example of small instance size showed promising results in minimising the total material handling cost composed of the weighted distances and material flow movements. The gap compared to the optimal solution was less than 0.85%.

In Chapter 4, ***research question Q3***[3] is answered. Retaining the same theoretical assumptions perviously stated, we then concentrated on near optimal solutions for the SRLP. On this, a new kind of meta-heuristic based on artificial bee colony algorithm, which was recently published for numerical optimisation problems and could be efficiently adopted for combinatorial optimisation problems, was analysed and enhanced. Due to its competitivness, we were motivated to extend the use of this approach to the area of

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[2] How does the integration of asymmetric, sequence-dependent clearances affect efficient construction heuristics for the SRLP?

[3] How can well-proven meta-heuristics be adapted for the SRLP with asymmetric, sequence-dependent clearances to obtain good quality solutions?

facility layout problems, particular to the SRLP for the first time. In contrast to the continuous nature of the original ABC algorithm, in the SRLP, a discrete permutation of n machines represents a food source and hence a solution. For this reason and additionally to be suitable for the asymmetric case of the SRLP with clearances, several elements of the ABC procedure had to be modified. This included mainly the way of generating feasible solutions in the initialising stage, the fitness evaluation which corresponds to the objective function value and has to consider the problem specific distance determination of asymmetric clearances, and, last, the order of the different phases of the ABC algorithm consisting of employed bees, onlooker bees and scout bees phase balancing the exploitation and exploration ability. Moreover, classical neighbourhood structures as they are common in SRLPs were incorporated in its search procedure. To evaluate the performance of the ABC algorithm, substantial computational experiments had been conducted for a wide range of problem sizes with up to 60 machines. Either compared to optimal or best known solutions, it has been shown that our variation of the ABC algorithm performs effectively and efficiently by attaining optimal solutions or deviating from best known solutions by 1.81 percent at most. Furthermore, the influence of different parameter settings on the near optimal solution was examined.

Finally, concerning our paper recently published and ***research questions Q4***[4] ***and Q5***[5], in Chapter 5, a new variation of the common SRLP in flexible manufacturing environments is proposed in which undesired interactions between machines may necessitate large clearances. Thus, clearances may not only be considered between adjacent machines, but also between machines arranged further away from each other. A detailed problem description was provided and illustrated the resulting difficult and challenging issue of arranging machines in the single row layout. In this case, clearances have to be satisfied which may span over several machines. Thus, for the same permutation, multiple absolute positions of machines are possible causing different distance matrices and objective values. Being more complex, the proposed model formulation was only able to optimally solve instance sizes with less than 10 machines in acceptable computational time. For larger sized problems, three different construction heuristics were developed and their performances was tested on several instances selected from literature or newly generated. All of them provided sufficiently good solutions with up to 100 machines in less than two seconds. Most advantageously, our heuristics suggested are more sophisticated since they incorporate the complete information of an instance given to generate a feasible solution (layout). That means, both the material flow as well as the length of machines and the respective

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[4] What effect does the integration of asymmetric, sequence-dependent and machine-spanning clearances have on the modeling of an appropriate SRLP?

[5] Does considering machine-spanning clearances require adjusted heuristics approaches for generating feasible solutions within computationally reasonable time?

clearances were considered in each iteration. Whereas most former constructive heuristics developed for FLP or SRLP use either only the material flow between machines (see, e.g., Heragu / Kusiak 1988, Kumar / Hadjinicola / Lin 1995) or only the length of machines (and clearances) in an instance (see, e.g., Samarghandi / Eshghi 2010, Hosseini Nasab / Kamali 2015).[6]

However, even though this work gives an extensive discussion and provides valuable insights into SRLPs considering different types of clearances, it points to several future research directions in this field. First of all, extensions regarding the solution approaches proposed in this thesis will be suggested.

Since the ABC algorithm presented in Chapter 4 was the first application to the SRLP, more thorough studies on different components of this novel meta-heuristic may yield better results and improve its overall performance. The quality of the initial solutions affects the performance of the algorithm. Therefore, to guarantee an initial population of bees with certain quality additionally to diversity, a part of food sources can be constructed by using problem-specific construction heuristics whereas the other part may be generated randomly as in the original algorithm. Another issue comprises the neighbourhood search mechanism. Our implementation of the ABC heuristic uses the simple and very common swap operator to generate feasible neighbouring solutions by interchanging two machines randomly selected. This forms the search space within the surrounding area of profitable food sources both for employed and onlooker bees. Since a proper defined neighbourhood is one of the most important steps in developing a meta-heuristic algorithm, a future research direction may include other neighbourhood structures such as 3-swap, insertion or block move strategies as they are used for instance in scheduling optimisation problems (cf. Pan et al. 2011, Han / Gong / Sun 2015). This may enhance the exploitation ability of the algorithm consisting of employed and onlooker bees phase. Related to this, onlooker bees select food sources depending on the strategy of a roulette wheel selection. With the purpose of improving the population diversity, several different selection schemes, such as tournament or rank selection, can be compared and integrated to the ABC for SRLP. Regardless which neighbourhood structure or selection scheme is choosen, more detailed analyses on the effects of parameter settings are worthwhile so as to optimise the trade-off between computational time and solution quality. In this part, only single row layouts with up to 60 machines have been tested and therefore further evaluations of our algorithm for larger instance sizes may be appreciated.

As the most obvious extension of the present work regarding the SRLP with machine-

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[6] One important exception is the heuristic of Djellab / Gourgand 2001 which we modified in order to integrate the case of asymmetric clearances.

spanning clearances, other heuristic solution methods should be applied to improve the inital single row layout constructed by one of our approaches. Thorough studies can be conducted to discover the most advantegeous meta-heuristic algorithm among the various amount of improving heuristics in SRLP or FLP. Moreover, a direction of work can be to give a comprehensive guidance regarding what kind of construction heuristic (random, problem-specific, etc.) is more appropriate to initialise meta-heuristics and to achieve high-quality layouts. Another research avenue is to apply the considerations of machine-spanning clearances to other production environments such as the double and the multi row layouts. Thus the results obtained from research of SRLPs may serve as a foundation. Then, modifications of established algorithms and novel solution approaches are needed.

In addition, reflecting our review, research on several aspects of SRLP are still in their initial stages or neglected to date. For instance, dynamic environments and considerations of uncertainty as common in other facility layout problems merit further investigations. We observed only a limited number of research in this field, notwithstanding the challenging issue in practice. Typically, input paramaters needed to generate an appropiate facility layout are not fully known, but predicted and thereby uncertain in most real-life manufacturing environments. To face uncertainty, the application of robust optimisation to the SRLP may be of particular interest in future studies since it is capable of improving the quality of the layout design. The aim of this approach is to find a machine placement that is acceptable and sufficiently good for different possible production situations with regard to the objectives pursued.

In general, the development and improvement of effective and efficient solution methods for the SRLP is still an open topic, especially meta-heuristics are of particular interest for solving large size instances in acceptable computational time. Supplement examinations may clarify whether best known exact solution approaches such as semidefinite programming are applicable to the case of asymmetric clearances owing to the lifted assumption of symmetric single row layouts. On this account, new benchmark instances should be added as many researchers still evaluate the performance of new solution approaches based on zero or constant clearances, although the model objective regards sequence-dependent (and asymmetric) clearances. A further point of interest may comprise to determine how an optimal solution can be obtained for larger problem sizes, irrespective whether clearances are considered or not and irrespective of the type of clearances included.

With regard to approximate algorithms, two different fruitful directions are observed. On the one hand, powerful restart mechanisms included in the course of a meta-heuristic as recently proposed by PALUBECKIS (2017) and GUAN / LIN (2016a) show promising results in exploiting the potential search space and generating competitive results. To prevent an algorithm by stagnating at or prematurely converging to a local optimum, restarting techniques are used to execute several independent searches from multiple starting points within the solution space and therefore guide the search into new regions of the solution space. Since these are the first studies related to restarts in SRLP, further research avenues may adress the issue of finding sophisticated restarting strategies (beside restarts from random initial solution), especially considering when and how a restart decisions should be made in the search process. On the other hand, different speed up techniques for an exhaustive neighbourhood search could significantly enhance both the solution quality and the time needed to solve an instance as e.g. introduced by KOTHARI / GHOSH (2013a), KOTHARI / GHOSH (2013b), GUAN / LIN (2016b) and should therefore be extended to different aspects of SRLP. These techniques are applied to determine the gain value of neighbouring solutions which is one of the most time consuming steps in meta-heuristics for the SRLP. A gain (move) is defined as the difference between the objective values of two neighbouring solutions. Depending on the neighbourhood structure involved, it accelerates the calculation process by considering only these parts of a single row (permutation) with changes in the machines sequence. Therefore, unnecessary recalculations are avoided. A similar speed-up technique may be used for other neighbourhood structures as well as implemented in other meta-heuristics as provided in SRLP literature so far.

Furthermore, future studies should continue to investigate the hybridisation of two or more meta-heuristic algorithms in order to achieve their benefits and to overcome their individual drawbacks.

With these possible extensions and future directions, the single row layout problem is still an interesting and worthwhile source for further researches.

Bibliography

AHMADI, A. / PISHVAEE, M. S. / JOKAR, M. R. A. (2017): A survey on multi-floor facility layout problems. In: *Computers & Industrial Engineering*, vol. 107, pp. 158–170.

ANEKE, N. / CARRIE, A. (1986): A design technique for the layout of multi-product flowlines. In: *International Journal of Production Research*, vol. 24, no. 3, pp. 471–481.

ANJOS, M. F. / KENNINGS, A. / VANNELLI, A. (2005): A semidefinite optimization approach for the single-row layout problem with unequal dimensions. In: *Discrete Optimization*, vol. 2, no. 2, pp. 113–122.

ANJOS, M. F. / VIEIRA, M. V. (2017): Mathematical optimization approaches for facility layout problems: The state-of-the-art and future research directions. In: *European Journal of Operational Research*, vol. 261, pp. 1–16.

ARIAFAR, S. / ISMAIL, N. (2009): An improved algorithm for layout design in cellular manufacturing systems. In: *Journal of Manufacturing Systems*, vol. 28, no. 4, pp. 132–139.

EL-BAZ, M. A. (2004): A genetic algorithm for facility layout problems of different manufacturing environments. In: *Computers & Industrial Engineering*, vol. 47, no. 2-3, pp. 233–246.

BENJAAFAR, S. / SHEIKHZADEH, M. (2000): Design of flexible plant layouts. In: *IIE Transactions*, vol. 32, no. 4, pp. 309–322.

BHASKER, J. / SAHNI, S. (1987): Optimal linear arrangement of circuit components. In: *J. VLSI COMP. SYST.*, vol. 2, no. 1, pp. 87–109.

Blum, C. / Li, X. (2008): Swarm Intelligence in Optimization. In: *Swarm Intelligence: Introduction and Applications*. Ed. by C. Blum / D. Merkle. Natural Computing Series. Berlin, Heidelberg: Springer Berlin Heidelberg. Chap. Swarm Intelligence, pp. 43–85.

Blum, C. / Roli, A. (2003): Metaheuristics in combinatorial optimization: overview and conceptual comparison. In: *ACM computing surveys (CSUR)*, vol. 35, no. 3, pp. 268–308.

Braglia, M. / Zanoni, S. / Zavanella, L. (2003): Layout design in dynamic environments: strategies and quantitative indices. In: *International Journal of Production Research*, vol. 41, pp. 995–1016.

Brunese, P. / Tanchoco, J. (2013): On implied within-building constraints for machine layout. In: *International Journal of Production Research*, vol. 51, no. 6, pp. 1937–1952.

Büyüksaatçi, S. (2015): Bat Algorithm Application for the Single Row Facility Layout Problem. In: *Recent Advances in Swarm Intelligence and Evolutionary Computation*. Ed. by X.-S. Yang. Volume 585. Studies in Computational Intelligence. Springer International Publishing, pp. 102–120.

Cheng, C. (1987): Linear placement algorithms and applications to VLSI design. In: *Networks*, vol. 17, no. 4, pp. 439–464.

Chiang, W.-C. / Chiang, C. (1998): Intelligent local search strategies for solving facility layout problems with the quadratic assignment problem formulation. In: *European Journal of Operational Research*, vol. 106, no. 2-3, pp. 457–488.

Chung, J. / Tanchoco, J. M. A. (2010): The double row layout problem. In: *International Journal of Production Research*, vol. 48, pp. 709–727.

Çil, I. / Evren, R. (1998): Linking of manufacturing strategy, market requirements and manufacturing attributes in technology choice: An expert system approach. In: *The Engineering Economist*, vol. 43, no. 3, pp. 183–202.

Das, S. K. (1993): A facility layout method for flexible manufacturing systems. In: *International Journal of Production Research*, vol. 31, no. 2, pp. 279–297.

Djellab, H. / Gourgand, M. (2001): A new heuristic procedure for the single-row facility layout problem. In: *International Journal of Computer Integrated Manufacturing*, vol. 14, no. 3, pp. 270–280.

Drira, A. / Pierreval, H. / Hajri-Gabouj, S. (2007): Facility layout problems: A survey. In: *Annual Reviews in Control*, vol. 31, no. 2, pp. 255–267.

Ficko, M. / Brezocnik, M. / Balic, J. (2004): Designing the layout of single- and multiple-rows flexible manufacturing system by genetic algorithms. In: *Journal of Materials Processing Technology*, vol. 157-158, pp. 150–158.

Friedrich, C. / Klausnitzer, A. / Lasch, R. (2018): Integrated slicing tree approach for solving the facility layout problem with input and output locations based on contour distance. In: *European Journal of Operational Research*, vol. 270 (3), pp. 837–851.

Gopal, S. J. / Gandhimathinathan, C. / Arunajadeswar, S. (2015): Modified artificial immune system for single row facility layout problem. In: *International Journal of Mechanical Engineering and Technology*, vol. 6, no. 6, pp. 52–59.

Guan, J. / Lin, G. (2016a): A multi-start local search algorithm for the single row facility layout problem. In: *International Journal of Innovative Computing, Information and Control*, vol. 12, no. 3, pp. 859–874.

Guan, J. / Lin, G. (2016b): Hybridizing variable neighborhood search with ant colony optimization for solving the single row facility layout problem. In: *European Journal of Operational Research*, vol. 248, no. 3, pp. 899–909.

Han, Y.-Y. / Gong, D. / Sun, X. (2015): A discrete artificial bee colony algorithm incorporating differential evolution for the flow-shop scheduling problem with blocking. In: *Engineering Optimization*, vol. 47, no. 7, pp. 927–946.

Heragu, S. S. / Gupta, Y. P. (1994): A heuristic for designing cellular manufacturing facilities. In: *International Journal of Production Research*, vol. 32, no. 1, pp. 125–140.

Heragu, S. S. / Kusiak, A. (1988): Machine layout problem in flexible manufacturing systems. In: *Operations Research*, vol. 36, no. 2, pp. 258–268.

Hosseini Nasab, H. / Fereidouni, S. / Fatemi Ghomi, S. M. T. / Fakhrzad, M. B. (2018): Classification of facility layout problems: a review study. In: *The International Journal of Advanced Manufacturing Technology*, vol. 94, no. 1, pp. 957–977.

Hosseini Nasab, H. / Kamali, H. R. a. (2015): A hybrid simulated annealing algorithm for single row facility layout problem. In: *International Journal of Industiral Engineering & Producion Research*, vol. 26, no. 4, pp. 243–253.

Hungerländer, P. (2014): Single-row equidistant facility layout as a special case of single-row facility layout. In: *International Journal of Production Research*, vol. 52, no. 5, pp. 1257–1268.

Hungerländer, P. / Rendl, F. (2013): A computational study and survey of methods for the single-row facility layout problem. In: *Computational Optimization and Applications*, vol. 55, no. 1, pp. 1–20.

Ioannou, G. (2007): An integrated model and a decomposition-based approach for concurrent layout and material handling system design. In: *Computers & Industrial Engineering*, vol. 52, pp. 459–485.

Ioannou, G. / Minis, I. (1998): A review of current research in manufacturing shop design integration. In: *Journal of Intelligent Manufacturing*, vol. 9, no. 1, pp. 57–72.

Joseph, O. / Sridharan, R. (2011): Evaluation of routing flexibility of a flexible manufacturing system using simulation modelling and analysis. In: *International Journal of Advanced Manufacturing Technology*, vol. 56, no. 1-4, pp. 273–289.

Kaku, B. / Rachamadugu, R. (1992): Layout design for flexible manufacturing systems. In: *European Journal of Operational Research*, vol. 57, no. 2, pp. 224–230.

Kalita, Z. / Datta, D. (2018): A constrained single-row facility layout problem. In: *The International Journal of Advanced Manufacturing Technology*, vol. In press, pp. 1–12.

Karaboga, D. / Gorkemli, B. (2011): A combinatorial Artificial Bee Colony algorithm for traveling salesman problem. In: *2011 International Symposium on Innovations in Intelligent Systems and Applications*, pp. 50–53.

Karaboga, D. (2005): An idea based on honey bee swarm for numerical optimization. Technical report. Engineering Faculty, Computer Engineering Department.

KAVEH, A. / SAFARI, H. (2014): Charged system search adopted for solution of traveling salesman problem: An application to single-row facility layout problem. In: *International Journal of Civil Engineering*, vol. 12, no. 3, pp. 363–370.

KELLER, B. (2019): Construction heuristics for the single row layout problem with machine-spanning clearances. In: *INFOR: Information Systems and Operational Research*, vol. 57, no. 1, pp. 32–55.

KELLER, B. / BUSCHER, U. (2015): Single row layout models. In: *European Journal of Operational Research*, vol. 245, no. 3, pp. 629–644.

KLAUSNITZER, A. / LASCH, R. (2016): Extended model formulation of the facility layout problem with aisle structure. In: *Logistics Management.* Ed. by D. MATTFELD / T. SPENGLER / J. BRINKMANN / M. GRUNEWALD. Springer International Publishing, pp. 89–101.

KOTHARI, R. / GHOSH, D. (2012): The single row facility layout problem: State of the art. In: *OPSEARCH*, vol. 49, no. 4, pp. 442–462.

KOTHARI, R. / GHOSH, D. (2013a): Insertion based Lin-Kernighan heuristic for single row facility layout. In: *Computers Operations Research*, vol. 40, pp. 129–136.

KOTHARI, R. / GHOSH, D. (2013b): Tabu search for the single row facility layout problem using exhaustive 2-opt and insertion neighborhoods. In: *European Journal of Operational Research*, vol. 224, pp. 93–100.

KOUVELIS, P. / CHIANG, W.-C. (1992): A simulated annealing procedure for single row layout problems in flexible manufacturing systems. In: *International Journal of Production Research*, vol. 30, no. 4, pp. 717–732.

KOUVELIS, P. / KURAWARWALA, A. / GUTIERREZ, G. (1992): Algorithms for robust single and multiple period layout planning for manufacturing systems. In: *European Journal of Operational Research*, vol. 63, no. 2, pp. 287–303.

KOUVELIS, P. / CHIANG, W.-C. / FITZSIMMONS, J. (1992): Simulated annealing for machine layout problems in the presence of zoning constraints. In: *European Journal of Operational Research*, vol. 57, no. 2, pp. 203–223.

Kumar, K. R. / Hadjinicola, G. C. / Lin, T.-l. (1995): A heuristic procedure for the single-row facility layout problem. In: *European Journal of Operational Research*, vol. 87, no. 1, pp. 65–73.

Kumar, S. S. / Kumar, R. M. S. (2016): Performance evaluation of proposed artificial immune system and improved sheep flock heredity algorithms for single row layout problem in flexible manufacturing system. In: *Asian Journal of Research in Social Sciences and Humanities*, vol. 6, no. 10, pp. 2221–2245.

Kusiak, A. / Heragu, S. S. (1987): The facility layout problem. In: *European Journal of Operational Research*, vol. 29, no. 3, pp. 229–251.

Lenin, N. / Siva Kumar, M. / Islam, M. N. / Ravindran, D. (2013): Multi-objective optimization in single-row layout design using a genetic algorithm. In: *The International Journal of Advanced Manufacturing Technology*, vol. 67, no. 5-8, pp. 1777–1790.

Lenin, N. / Mahalingam, S. K. / Gurusamy, S. / Dharmaraj, V. K. (2018): Solution for bi-objective single row facility layout problem using artificial bee colony algorithm. In: *European Journal of Industrial Engineering*, vol. 12, no. 2.

Leung, J. (1992a): A new graph-theoretic heuristic for facility layout. In: *Management Science*, vol. 38, pp. 594–605.

Leung, J. (1992b): A graph-theoretic heuristic for designing loop-layout manufacturing systems. In: *European Journal of Operational Research*, vol. 57, no. 2, pp. 243–252.

Maadi, M. / Javidnia, M. / Ghasemi, M. (2016): Applications of two new algorithms of cuckoo optimization and forest optimization for solving single row facility layout problem. In: *Journal of AI and Data Mining*, vol. 4, pp. 35–48.

Manzke, L. / Keller, B. / Buscher, U. (2018): An artificial bee colony algorithm to solve the single row layout problem with clearances. In: *Information Systems Architecture and Technology: Proceedings of 38th International Conference on Information Systems Architecture and Technology – ISAT 2017*. Ed. by Z. Wilimowska / L. Borzemski / J. Świątek. Advances in Intelligent Systems and Computing 657. Springer International Publishing, pp. 285–294.

Mayer, B. / Buscher, U. (2012): Einbeziehung von Mindestabständen in das eindimensionale Maschinenlayoutproblem. In: *Innovative Produktionswirtschaft*. Ed. by C. Mieke / D. Braunisch. Berlin: Logos Verlag, pp. 131–149.

Meller, R. / Gau, K. (1996): The facility layout problem: recent and emerging trends and perspectives. In: *Journal of Manufacturing Systems*, vol. 15, no. 5, pp. 351–366.

Mernik, M. / Liu, S.-H. / Karaboga, D. / Črepinšek, M. (2015): On clarifying misconceptions when comparing variants of the Artificial Bee Colony Algorithm by offering a new implementation. In: *Information Sciences*, vol. 291, pp. 115–127.

Murthy, P. / Ranganayakulu, J. / Vidhu, K. / Rao, K. V. (2016): Heuristic search algorithm for the single-row machine layout in an automated manufacturing system. In: *Procedia Technology*, vol. 25, pp. 1088–1095.

Nearchou, A. C. (2006): Meta-heuristics from nature for the loop layout design problem. In: *International Journal of Production Economics*, vol. 101, no. 2, pp. 312–328.

Ning, X. / Li, P. (2017): A cross-entropy approach to the single row facility layout problem. In: *International Journal of Production Research*, vol. 56, no. 11, pp. 3781–3794.

Ozcelik, F. (2012): A hybrid genetic algorithm for the single row layout problem. In: *International Journal of Production Research*, vol. 50, no. 20, pp. 1–15.

Palubeckis, G. (2012): A branch-and-bound algorithm for the single-row equidistant facility layout problem. In: *OR Spectrum*, vol. 34, pp. 1–21.

Palubeckis, G. (2015a): Fast local search for single row facility layout. In: *European Journal of Operational Research*, vol. 246, no. 3, pp. 800–814.

Palubeckis, G. (2015b): Fast simulated annealing for single-row equidistant facility layout. In: *Applied Mathematics and Computation*, vol. 263, pp. 287–301.

Palubeckis, G. (2017): Single row facility layout using multi-start simulated annealing. In: *Computers & Industrial Engineering*, vol. 107, pp. 1–16.

PAN, Q.-K. / TASGETIREN, M. F. / SUGANTHAN, P. / CHUA, T. (2011): A discrete artificial bee colony algorithm for the lot-streaming flow shop scheduling problem. In: *Information Sciences*, vol. 181, no. 12, pp. 2455−2468.

PICARD, J.-C. / QUEYRANNE, M. (1981): On the one-dimensional space allocation problem. In: *Operations Research*, vol. 29, no. 2, pp. 371−391.

PILLAI, V. M. / HUNAGUND, I. B. / KRISHNAN, K. K. (2011): Design of robust layout for dynamic plant layout problems. In: *Computers & Industrial Engineering*, vol. 61, pp. 813−823.

POURVAZIRI, H. / PIERREVAL, H. (2017): Dynamic facility layout problem based on open queuing network theory. In: *European Journal of Operational Research*, vol. 259, no. 2, pp. 538−553.

RUBIO-SÁNCHEZ, M. / GALLEGO, M. / GORTAZAR, F. / DUARTE, A. (2016): GRASP with path relinking for the single row facility layout problem. In: *Knowledge-Based Systems*, vol. 106, pp. 1−13.

SAMARGHANDI, H. / ESHGHI, K. (2010): An efficient tabu algorithm for the single row facility layout problem. In: *European Journal of Operational Research*, vol. 205, no. 1, pp. 98−105.

SAMARGHANDI, H. / TAABAYAN, P. / JAHANTIGH, F. F. (2010): A particle swarm optimization for the single row facility layout problem. In: *Computers & Industrial Engineering*, vol. 58, no. 4, pp. 529−534.

SARAVANAN, M. / KUMAR, S. / RAJKUMAR, M. (2016): Design and optimisation of single row layout problem in flexible manufacturing systems using metaheuristic algorithms. In: *International Journal of Manufacturing Technology and Management*, vol. 30, no. 3-4, pp. 196−215.

SIMMONS, D. M. (1969): One-dimensional space allocation: an ordering algorithm. In: *Operations Research*, vol. 17, no. 5, pp. 812−826.

SINGHOLI, A. / CHHABRA, D. / ALI, M. (2010): Towards improving the performance of flexible manufacturing system: a case study. In: *Journal of Industrial Engineering and Management*, vol. 3, no. 1, pp. 87−115.

SOLIMANPUR, M. / VRAT, P. / SHANKAR, R. (2005): An ant algorithm for the single row layout problem in flexible manufacturing systems. In: *Computers & Operations Research*, vol. 32, no. 3, pp. 583–598.

SRINIVAS, C. / REDDY, B. R. / RAMJI, K. / NAVEEN, R. (2014): Sensitivity analysis to determine the parameters of genetic algorithm for machine layout. In: *Procedia Materials Science*, vol. 6. 3rd International Conference on Materials Processing and Characterisation (ICMPC 2014), pp. 866–876.

SURYANARAYANAN, J. / GOLDEN, B. / WANG, Q. (1991): A new heuristic for the linear placement problem. In: *Computers & Operations Research*, vol. 18, no. 3, pp. 255–262.

TUBAILEH, A. S. (2014): Layout of flexible manufacturing systems based on kinematic constraints of the autonomous material handling system. In: *The International Journal of Advanced Manufacturing Technology*, vol. 74, no. 9, pp. 1521–1537.

TUBAILEH, A. S. / SIAM, J. (2017): Single and multi-row layout design for flexible manufacturing systems. In: *International Journal of Computer Integrated Manufacturing*, vol. 30, no. 12, pp. 1316–1330.

TUZKAYA, G. / GÜLSÜN, B. / TUZKAYA, U. R. / ONUT, S. / BILDIK, E. (2013): A comparative analysis of meta-heuristic approaches for facility layout design problem: a case study for an elevator manufacturer. In: *Journal of Intelligent Manufacturing*, vol. 24, no. 2, pp. 357–372.

XIE, W. / SAHINIDIS, N. V. (2008): A branch-and-bound algorithm for the continuous facility layout problem. In: *Computers & Chemical Engineering*, vol. 32, no. 4-5, pp. 1016–1028.

YEH, W. C. / LAI, C. M. / TING, H. Y. / JIANG, Y. / HUANG, H. P. (2017): Solving single row facility layout problem with simplified swarm optimization. In: *13th International Conference on Natural Computation, Fuzzy Systems and Knowledge Discovery (ICNC-FSKD)*, pp. 267–270.

YU, J. / SARKER, B. R. (2003): Directional decomposition heuristic for a linear machine-cell location problem. In: *European Journal of Operational Research*, vol. 149, no. 1, pp. 142–184.

Yu, M. / Zuo, X. / Murray, C. C. (2014): A tabu search heuristic for the single row layout problem with shared clearances. In: *2014 IEEE Congress on Evolutionary Computation (CEC)*, pp. 819–825.

Zuo, X. Q. / Murray, C. C. / Smith, A. E. (2016): Sharing clearances to improve machine layout. In: *International Journal of Production Research*, vol. 54, no. 14, pp. 4272–4285.