2014

A New Approach for Generating Facility Layouts Using an Algorithmic Approach

Volker Sadowsky
TU Dortmund University, volker.mattick@tu-dortmund.de

Christian Mosblech
TU Dortmund University

A NEW APPROACH FOR GENERATING FACILITY LAYOUTS USING AN ALGORITHMIC APPROACH

Christian Mosblech
Chair of Materials Handling and Warehousing
Faculty of Mechanical Engineering
TU Dortmund University
Dortmund, Germany

Volker Sadowsky
Chair of Materials Handling and Warehousing
Faculty of Mechanical Engineering
TU Dortmund University
Dortmund, Germany

Abstract

In this paper a new approach is described to automatically create layouts for material flow systems. The current research in progress aiming at adopting the methods and algorithms of the Electronic Design Automation to be used in logistics planning is presented. These methods are already applied to create microchips being multiple times more complex than material flow systems while following the same goal: Functional units have to be placed on a predefined area and are linked by connections weighted differently. This basic requirement can be applied to microchip designs as well as material flow systems. The common condition is to create the setup with the smallest connection length possible.

The results are compared to a currently applied computerized method to calculate facility layouts. The overall result of the introduced method is nearly equal to the traditional reference method to create a computerized material flow layout. However, while the new algorithm does all calculations automatically, the traditional method requires manual finishing to achieve a comparable result.

This article thereby shows the potential of the research in progress toward the goal to support logistics planning with a new generation of automated software tools.

1 Introduction

Creating an optimized facility layout for a material flow system is one of the main tasks in almost every planning process. These processes are structured and organized by different methods and strategies splitting the overall process into multiple single steps. One of those is always the creation of a layout having an optimized material flows ([1], [2], [3]). Although creating a material flow layout is included in all these planning methods, the tools and algorithms actually used are not on the level of the current research and technical possibilities. Basic algorithms like CRAFT ([4]) or heuristics like the triangle generation of Schmigalla ([5]) are originated in the last century. This includes the adaption of these heuristics to the computerized resources available back then. Since this technology has strongly advanced, the layout algorithms have concurrently been further optimized without implementing a completely new approach. Thereby, the available potential of the current computer generation including additional features like parallel processing, huge amounts of physical and virtual storage capacity and the raw processing power is not fully utilized by the existing layout generation algorithms.

The use of such resources allows efficient processing of large amounts of data as included in the tasks of intralogistics planning. In order to satisfy customer demands like decreasing the number of units while increasing their level of individuality, the complexity of logistics systems has been escalating in the past years. Logistic processes have to be more flexible resulting in shortened planning periods for creating new or evolving existing systems. Under such circumstances manual planning processes are too time consuming while they take up days or weeks whereas the considered systems have to react within merely hours on changing determining factors. According to current research the future logistics and production systems will be modular to a certain degree ([6, 7, 8]). This makes changes to the whole system on a just-in-time basis depending on customer orders possible. Therefore, planning results especially in the field of layout generation are required to be available on short notice. Alternatively, the monetary advantages of those modular systems can be erased by rising costs for the material handling.

The general goal is to develop a highly automated method to create possible layouts to a given material flow system. In the best case the ongoing research in this field of expertise will lead to a system to generate optimal material flow layouts at the push of a button. The means to describe such a system are chosen in accordance to the commonly used tools and data representations in the logistics planning process such as transportation matrices or area specifications for material flow components.

This article presents the results of an ongoing research project and presents the first breakthroughs made. It describes the fundamental mathematical problem to be solved by a layout generation process. This description is followed by an overview of heuristics to solve the layout creation processes currently in use. Additionally, the shortcomings of current methods are highlighted. This enumeration shows the requirement for creating a new approach for the layout generation with an easy to use and easy to understand approach on the one hand and the possibility to create optimal layouts in a short time on the other hand. This new approach is introduced in the subsequent part of this article. The method makes use of the research results in another field of work having the same fundamental problem on a larger scale: the Electronic Design Automation (EDA). This field combines the methods and algorithms to create complex digital circuits placed on a microchip. After presenting basic process model of the EDA, the first implementations and adaptions into intralogistics planning are brought forward. After first promising validations, this article closes with the perspective on further research work in this area.

2 Basic Problem

The general problem while creating a material flow layout is aiming for an optimal material flow while using the minimal amount of space possible with all components placed. Additionally, there are multiple more determining factors raising the complexity of the general calculation even further. These factors can range from obvious ones like prohibiting overlaps during the planning process to complex legal regulations e. g. in the field of chemical production or the food industry. One of the most common goals of the facility layout is to minimize the transport costs required for the material flow system to work properly ([9]).

Creating a valid layout for a material flow system shall be described as a mathematical problem. This problem is defined as the Factory Layout Problem (FLP) described in the following formula:

$$\sum_{i=1}^{n}\sum_{j=1}^{n} f_{ij} c_{ij} d_{ij}$$

with
n: number of components in the material flow system
f_{ij}: the material flow between the components i and j
c_{ij}: the cost for the transport between components i and j
d_{ij}: the distance between the components i and j ([2, 9])

To create a valid layout only the matrix containing all distances d_{ij} is optimized while the other influences are untouched. Those parts of the formula originated from the project data pool or their values are the result of decisions within the planning process like the conveying system to be deployed. Solving the mathematical problem however results in either long calculation times or imprecise outcomes depending on the algorithm used.

Another constraint to this fundamental solution is the absence of additional conditions to the calculation. For example, placing two functional units directly besides each other is only a random outcome based on the overall material flow and cannot be controlled by the input parameters. The requirement to do so can be shown by an obvious example, like placing the incoming goods process of an intralogistics system near the delivery gates of the facility. Without defining the special connection between these two components explicitly, the placement is only depending on the transport intensity in between.

These shortcomings have led to different solutions currently applied in logistics planning processes being presented thereafter.

3 Current Practices and Research

Currently there are multiple methods and algorithms available allowing the creation of layouts for intralogistics and production systems. One possible classification of these methods can be achieved by focusing on the required calculations enabling a manual planning or involving computerized support. Additionally, there are recent developments solving the fundamental problem with completely new approaches.

3.1 Manual planning procedures

Manual planning methods enable the planner to create viable layouts within a short period of time. Normally these methods solve the general problem to create a facility layout in early planning stages. The most basic solutions require the planner to produce models of the material flow components from paper or cardboard and place them inside a given area. This approach is supported by modern CAD software applications by allowing creating the placement virtually. Some advances have been made using heuristics structuring this manual placement process. Two of those are the friction circle method by Schwerdtfeger and triangular method by Schmigalla ([5, 10]).

In contrast to the simple means to create layouts with these methods there are several disadvantages, such as the required amount of time, the lack of precision and the disability to cope with determining factors directly. These shortcomings make sure that the manual procedures are mostly used in a very early planning stage. They are not able to create layouts sophisticated enough to be directly implemented. In case of the triangular method, they are unable to handle loops in the material flow. Additionally, these procedures depend strongly on the expertise of the executing planner. Without knowledge and expertise, creating a material flow layout resembles trial and error and does not follow an organized and structured pattern.

3.2 Automated planning algorithms

The algorithms in this group make use of computerized resources to create layouts for material flow systems. Therefore, these methods can calculate layouts more efficiently creating results nearer to the optimal solution for a given facility layout task. Their central advantage is making use of the capability to calculate numerous equations simultaneously enabling even trial and error based algorithms or the complete enumeration of potential solutions for small material flow systems to be executed in a short amount of time.

One of the first algorithms being developed is the Computerized Relative Allocation of Facilities Technique (CRAFT) algorithm. It was originated in the 1960s and was first described in [11] by G. C. Armour and E. S. Buffa. Basically this method cuts given functional units into parts having the size of a pre-defined rectangular pattern. Following an initial placement setup is created by guessing a valid layout result. In the actual calculation phase the algorithms tries to find pairs of components reducing the overall transportation cost if exchanged. If such a pair is discovered, all involved parts are exchanged.

The CRAFT algorithm in its basic form has one main disadvantage. It may not be able to keep the rectangular form of the material flow components during the runtime. This originates from the exchange of functional units with unequal sizes. To create enough free space for the larger exchange partner, a noninvolved third component has to be modified. Because only so many parts are moved as required to place the exchanged unit, this can lead to the dissolving of the original rectangular form. This can lead to "L"- or "T"-shaped placement propositions. Besides, by exchanging parts of the element after these have been cut to the minimal possible raster size can lead extreme aspect ratios. In the worst case this can result to valid layouts concerning the minimal material flow which are impossible to implement in the real world. An example is the placement of an automated store and retrieval system on an area of two meters by 100 meters. Even creating one aisle between two shelves is not possible.

Regardless of these shortcomings, the basic CRAFT algorithm has been the origin for further research. These attempts tried to improve results or the calculation duration or even to overcome the known problems of the basic algorithm ([12, 13]). However, this research does not change the fact that the algorithm was created to run on mainframe computers having been state of the art in the early 1960s. Modern computer systems have not only increased the amount of possible calculations per second resulting in a faster calculation, but also technologies like parallel processing have been introduced with the repetitive exchange of functional units being not able to gain from them.

3.3 Recent Research results

In the last decade additional research aimed to solve the facility layout problem by using completely new ways. Methods having been developed, which are adopting models from fields of research different to the intralogistics in order to solve the fundamental problem. Promising results are published using a Taboo-Search algorithm on slicing trees, a co-evolutionary algorithm or even mapping the fundamental problem to an ant-colonization optimization [9, 14, 15]. Even transferring production and material flow systems to the metabolism of cells is currently in research and the creation of optimal layouts can be one of the possible outcomes [16].

All these methods are no longer comprehensible in detail for the planner and require solemnly advanced computer systems to function. Possible occurring errors cannot be traced easily, especially if there are already inconsistencies in the input data to the calculations.

3.4 Research gap

Each mentioned method or algorithm has shortcomings limiting its respective use. Not one of the algorithms or heuristics is able to cope with the claimed requirements modern layout generation dictates to the planner. The creation of layouts for material flow or production systems has to be created nearly instantaneously making use of data commonly available to a logistics planner. This allows modern intralogistics systems to be optimized according to their flexibility and modularity.

4 New Approach

The fundamental problem of placing components on a predefined area or at least within the smallest amount of occupied space can be found in other fields of work besides intralogistics planning. In some of these, the considered problems exceed the facility placement by far in terms of size and connection complexity. One solution to the fundamental placement problem can be found in the field of Electronic Design Automation (EDA).

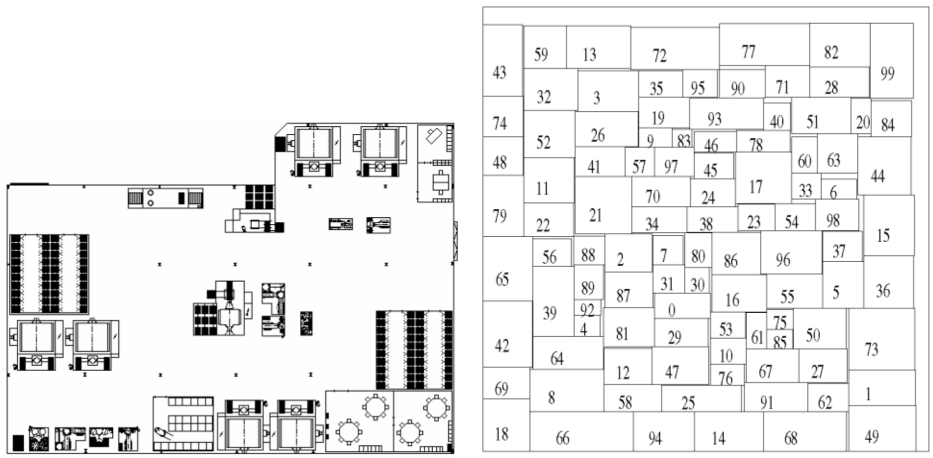
EDA is a name for the algorithms and applications enabling the creation of modern integrated circuits ([18]). Due to the number of components contained on one microprocessor, manual designing is not possible. In 2011 NVIDIA Corp. claimed to have placed 3.0 billion transistors on a single GPU ([19]). While the complexity of modern microchips has not stopped increasing since and the technologies to produce such devices become more and more sophisticated, the transistor count is increasing nowadays. This characteristic of a microchip is even used as an indicator for the complexity and capabilities of the embedded circuits.

Figure 1 shows an example for a material flow system (figure 1a) and a microchip design (figure 1b) obviously showing the similarities in the placement. Simultaneously, this example hints at the increased complexity of creating a valid and optimized microchip layout. The microchip contains a placement for a higher component count than the shown material flow system.

4.1 Basic Modeling Process

The basic process to create a microchip layout has no single definition. The implemented methods vary in their structures and details ([20], [21], [22]). There are similarities however, resulting in five basic steps leading to a microchip layout. These steps are displayed in figure 2.

The “Partitioning” step in the creating process reduces the overall complexity of the placement problem. To achieve this, the problem modeled as a graph $G = \{V, E\}$ where the vertices V represent single components and the edges E their defined connections. This graph is broken into sub-graphs called partitions with the condition that the number of edges cut by all partition borders is minimized. Simultaneously, this implies that the inner edges by comparison represent stronger bounds within the partitions ([21]).



(a) Material flow layout having all components placed ([2])

(b) Microchip layout containing placed calculation cells ([17])

Figure 1: Comparison of a material flow system (1a) and a microchip layout (1b)

The step “Floorplanning” is used to place the partitions on a predefined area, resulting in a first layout of the microchip. In this step the exact shapes and measurements for each partition are defined also. Generally this task provides the (approximate) coordinates for all partitions being created in the previous step ([23, 21]).

Within the "Placement", the individual components are placed within their corresponding partitions. This step implies that the pin assignment is being generated, meaning a location for exterior connections inside the partitions is determined. Additionally, the algorithms used to create the previous floor plan can be used to calculate to placement inside the partitions.

The “Routing” creates actual connections between the components. In some cases this step is divided into a rough and fine routing but the outcome is always a plan for the wiring inside the microchip ([21]).

When all elements of the microchip are defined and placed within the given limits, the whole resulting setup is compacted. This includes a global optimization eliminating the still remaining free spaces and results in the finished definition of the embedded circuit.

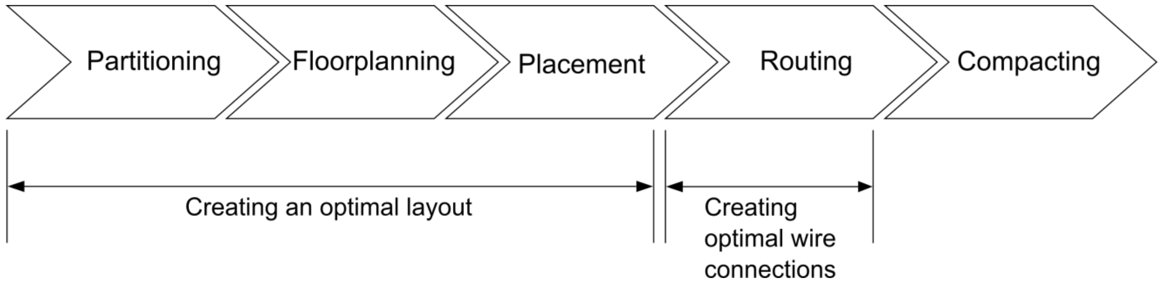


Figure 2: Basic process to create a microchip design

The central task for the current research is to map the input, the determining factors and the outcome to intralogistics systems. This includes the creation of analogies for every single component used in the process as well as implementing simplifications to the overall procedure. An example to reduce the complexity is the possibility to use one conveyor system to transport multiple goods while a placed wire inside a microchip can only deliver one single signal.

As this article describes current research in progress only the first process steps in the EDA setup have been implemented so far.

4.2 Adopting Partitioning

There are two different types of algorithms solving the partitioning problem. The first group creates two sets of nodes on a given graph $G = \{V, E\}$ using different optimization methods after creating an initial guess. Thereby these algorithms are limited to an output of two partitions. Every other solution has to be calculated by running the algorithm on the results of a prior run creating two new partitions on each generated set. This leads to an optimal partitioning only in the case, if the required number of partitions is included in the sequence $a_n = 2^n$. Elsewise the resulting partitions vary in size. Examples for such algorithms are Kernighan-Lin or Fiduccia-Mattheyses ([24, 25]).

The second type of algorithms creates k partitions simultaneously, whereat the k value is specified by the user. The created partitions are about the same size and again the internal edges represent stronger bonds than the external ones. To calculate the optimal set of these partitions there are two possible approaches. On the one hand the basic bi-partitioning algorithms are modified to cope with more than two partitions [26]. On the other hand a spectral analysis of the eigenvectors of the matrix derived from the material flow graph can be used to create the optimal partitioning [27, 28].

In addition, the graph representation of a material flow system is augmented by adding values to the edges resulting in a graph with weighted edges $G = \{V, E, g(e)\}$. The added term $g(e) \to \mathbb{R}$ is used to assign a real value to every edge in the graph. The function maps the transports intensities of the material flow system to the edges in the corresponding graph representation. In contrast to the original algorithms the transports between material flow components can differ regarding their intensity. At the same time, this function can be used to evaluate the cuts created by partitioning the material flow graph. The task of the partitioning algorithms is therefore modified. It searches for the partitioning cutting the smallest sum of transport intensities instead of the smallest number of connections. This creates partitions with strong internal material flows while all streams to other partitions are smaller by direct comparison.

Both ways to calculate k partitions have been reviewed to find the best solution for partitioning material flow systems. Coping with multiple or weighted connections is not possible in every case and calculating the eigenvectors to a degree of k requires a vast amount of calculation time. A compromise between calculation efficiency and accuracy is introduced by [29, 30]. In the proposed algorithm a helpful set is calculated from eigenvectors and used as a base for the exchange heuristic of Kernighan-Lin. Tests have determined that this algorithm is able to handle the common data sizes of material flow systems while creating optimal partitions.

4.3 Implementing the Floorplanning

The floorplanning step uses algorithms to place the prepared partitions on a user defined area. There are several ways to create these placements. One possibility is the use of slicing trees introduced in 1983 ([31]). This method to place components on a defined area is already applied onto intralogistics systems ([9]). Other ways to create floor plans are the cluster-growth-algorithm ([21]) or the linear order algorithm ([32]).

Another possible way to create a layout is using an analytic approach. All determining factors are mapped to formulas describing their innermost restrictions. The results are integrated into an analytic approach to calculate the placement. This approach adapts the fundamental optimization problem and reduces it to a solvable mathematical system [17]. It calculates the final floor plan by minimizing the following formula:

$$F = WL + \alpha P_D + \beta B$$

with:
WL: the wire length between all components
P_D: penalty term gaining with a high overlap of the components
B: penalty term gaining when components leave the predefined area
α: control value for the influence of P_D
β: control value for the influence of B ([17])

This optimization can be solved by using nonlinear optimizations like the proposed conjugate gradient method [17]. These algorithms allow for fast execution times compared to alternative methods like the Simplex-Algorithm.

Additionally, this general approach allows for raised flexibility due to the possibility to add and remove penalty terms according to the determining factors. The only requirement for additionally introduced terms is the property to be continuously differentiable.

5 First validation Results

The first two steps of creating a layout using the methods of the Electronic Design Automation have been successfully mapped to intralogistics planning and implemented as a software application. In the process the required input data has been adopted to fit commonly used description forms for material flow systems. The resulting software application creates a graph representing the system internally, if at least provided with a transportation matrix. Using this material flow graph, partitions can be calculated and the values of the necessary cuts can be optimized. This optimization can be configured to focus on two aspects: Being executed aiming at the best overall execution time or at creating the calculation of an optimal material flow. If the execution time is to be optimized, the partitions are chosen to balance the calculations of the floorplanning and the partitioning steps. This approach aims at nearly equal runtimes concerning the two steps. If the material flow is optimized, the partition set with the smallest external connection count has to be calculated resulting in the strongest interconnected material flow components to be placed in short distance to each other. This means the partitioning is done in the most efficient way concerning the material flow.

In order to calculate the second step, the dimensions of the included functional units have to be determined. These values are developed in the planning process, for instance by determining the capacity of the storage system or calculating the required order picking performance.

To test the overall performance of the developed algorithm and compare it to established methods, a first benchmark is used. The transportation matrix including the floor space required is presented in table 1. Additionally, the facility area is defined as being ten by ten units in size. There are no restrictions to the placement given. Due to the fact that only the floorplanning step is to be validated, the partitioning of the material flow graph is configured to create 10 partitions containing one functional unit each.

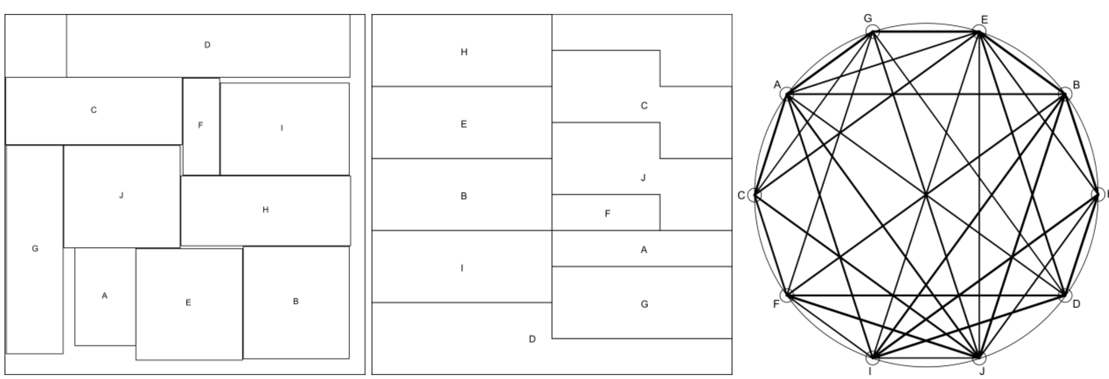
Table 1: Transportation matrix used to evaluate the algorithms

Component	*A*	*B*	*C*	*D*	*E*	*F*	*G*	*H*	*I*	*J*	*Size*
A		14		77			15		15	16	5
B	14				17	15		19	17		10
C	18				15		11			12	10
D	12				16	16	11	19	18		15
E	13	19					19	13		11	10
F			15							18	3
G	19					12				14	10
H		12			11				18		10
I	15			18	12	12				11	10
J	13	18	16			18		13			10

This data has been inserted into the test bed implementation and the automated layout creation has been performed. The automatically created result is shown in figure 3a. In order to validate this result another run of the software was executed using the basic CRAFT algorithm. As it is visible in figure 3b, the provided test scenario leads to a layout almost unable to implement in real live. Especially the functional units “C” and “J” have lost their rectangular shape while being optimally placed. This may result in a layout solution, which cannot be put into practice by logistics trades depending on the flexibility of the individual components.

Calculating the problem with manual means like the circle and triangular method shows the advantage of the computerized layout generation. The triangular method is unable to cope with the loops in the material flow defined in the transportation matrix. So there is no valid result to the given problem. As seen in figure 3c the circle friction method can create a proposal, how the layout can be distributed. Due to the similar dimension of all used material flow intensities and the complex material flow setup, the result does not show a practical way to place functional units inside a given area.

A directly comparable outcome parameter is the overall transportation length being weighted according to the transportation matrix. This leads to a single value for the layout created with EDA and a value for the setup calculated by CRAFT. The resulting distances between two functional units are visible in tables 2 and 3. The weighted overall transport length is 2740.00 units calculated by the EDA algorithms and 2445.10 units using CRAFT. This means the CRAFT algorithm has created a solution about 10.8% better than the new algorithm.



(a) Benchmark result created by algorithms following EDA design rules

(b) Alternative result created with the CRAFT algorithm

(c) Placement proposition generated with the circle method of Schwerdtfeger

Figure 3: Comparison of generated layouts created using the EDA approach (3a), the CRAFT algorithm (3b) and the circle method of Schwerdtfeger (3c)

A possible reason for this discrepancy is up to regarding only barycenters of all functional units to calculate the transportation distance. Especially the non-rectangular shapes have focal points better suited for this kind of distance calculation. Additionally, a systematic influence resulting from the single scenario being better suited for the CRAFT solving strategy is possible. If the CRAFT result is manually mapped to rectangle shaped functional units, the resulting length elongates to 2549.96 units being only 6.9% difference to the new approach.

Although the first benchmarks resulted in a slightly raised transportation intensity compared to traditional planning methods, the overall potential of the new way to create layouts is obvious. Due to its mathematical approach, new restrictions can be applied solemnly by adding corresponding penalty terms to the minimization formula. This results in a raised flexibility concerning its use in the process of planning material flow systems. This advantage will be balancing the slightly longer transport. Additionally, the used calculation algorithms can be optimized in itself to create better results.

6 Conclusion and further Work

The results presented in the article show the potential benefits for the planning of intralogistics systems. The required amount of time and the expertise needed to create a facility layout supporting an optimal material flow can be reduced compared to the manual realization. Additionally, already in the presented first examples, problems with the old creation methods like sticking to rectangular shapes can be overcome.

While further pursuing the current research, the creation of material flow layouts with the algorithms used in the field of Electronic Design Automation can result in a software application allowing for almost automatic layout generation. It can propose layouts optimal to the provided data and restrictions for the planner to choose from. The calculations used to create the layouts will be optimized in further research to reach a higher quality within reduced execution time.

Additionally, further automated benchmarks will be implemented and calculated. A collection of material flow systems applicable as such benchmarks is defined in [9] including the results and detailed execution data. If succeeding in creating layouts for all given benchmarks, the new method has to compete against manual planning of experienced planners. Real planning projects will be taken into account and the created placements compared to the calculated results of the software.

In the next implementation step, the detailed placement and wiring algorithms have to be implemented. This enables the resulting software not only to generate layouts, but also to calculate the material flow paths simultaneously. This includes the actual conveyor paths which replace the virtual distance measuring from the central point of one component to another. This will create a completely new paradigm in the automated or computer aided planning: While the common methods only create layouts, the EDA algorithms provide the means to calculate placements and their connections in form of wiring in one process. To define analogies between single point-to-point connections and transportation systems allowing multiple reuses is the challenge in these next steps.

Table 2: Resulting distances using EDA

Component	*A*	*B*	*C*	*D*	*E*	*F*	*G*	*H*	*I*	*J*
A		5.54		7.87			2.47		7.12	2.95
B	5.54				3.11	5.81		2.81	5.05	
C	5.40				6.25		4.37			2.62
D	7.87				7.25	2.35	7.77	5.07	3.28	
E	2.44	3.11					4.76	3.51		3.69
F			3.15							3.07
G	2.47					6.01				2.96
H		2.81			3.51				2.44	
I	7.12			3.28	5.79	2.43				5.12
J	2.95	5.93	2.62			3.07		4.20		

Table 3: Resulting distances using CRAFT

Component	*A*	*B*	*C*	*D*	*E*	*F*	*G*	*H*	*I*	*J*
A		5.22		3.64			1.51		5.03	2.03
B	5.22				2.00	4.03		4.01	1.97	
C	4.03				4.99		5.53			2.00
D	3.64				6.45	3.86	2.83	8.33	3.11	
E	6.10	2.00					7.08	2.01		5.15
F			3.19							1.37
G	1.51					2.69				3.56
H		4.01			2.01				6.00	
I	5.03			3.11	4.00	4.23				5.51
J	2.03	4.93	2.00			1.37		6.08		

While researching and implementing the above algorithms already the partitioning itself has shown an impact on logistics planning. If a planning scenario is further detailed by adding all material flows reaching and leaving a functional unit, even the returned empties and the required maintenance, the partitioning can result in new ways to group functional units. If these flows are weighted correctly, the partitioning results in groups having strong bounds independent from functionally influenced planning behavior. This theory will be researched further parallel to the generating of new layouts.

All in all, we are certain that pursuing the presented approach to create material flow layouts will result in useful new methods for intralogistics planning. Aiming at the long term goal to create a method pool to support every logistics planning project to an almost automatic degree is supported with this new approach. Combined with tools to calculate storage and process dimensions as well as means to analyze basic data automatically, the presented approach will result in a new working field for planners. Instead of redoing repetitive tasks for every project the fundamental work will be automated while the planner adds the creative input to create efficient and sustainable material flow systems.

Acknowledgements

The project funding of the presented research is provided by the EUROPEAN UNION - European Regional Development Fund (ERDF), the Ziel2.NRW-Program and the department "Ministerium für Wirtschaft, Energie, Industrie, Mittelstand und Handwerk des Landes Nordrheinwestfalen".

References

[1] ten Hompel, M., Schmidt, T. and Nagel, L., *Materialflusssysteme - Förder- und Lagertechnik*, Springer-Verlag Berlin Heidelberg (2007).

[2] Arnold, D. and Furmans, K., *Materialfluss in Logistiksystemen*, Springer Heidelberg Dordrecht London New York (2009).

[3] M. Heinecker, Methodik zur Gestaltung und Bewertung wandelbarer Materialflusssysteme, Ph.D. dissertation, Technische Universität München (2006).

[4] Buffa, E. S., Armour, G. C. and Vollmann, T. E., "Allocating facilities with CRAFT," *Harvard Business Review*, 42, 2, 136-158 (1964).

[5] Schmigalla, H., *Methoden zur optimalen Maschinenanordnung,* VEB Verlag Technik, Berlin (1970).

[6] Buchholz, S., "Future manufacturing approaches in the chemical and pharmaceutical industry", *Chemical Engineering and Processing: Process Intensification*, 49, 10, 993-995 (2010).

[7] Follert, G., Margareta, L., and ten Hompel, M., "Design Approach to Create Transformable Material Flow Systems," *Sustainability and Collaboration in Supply Chain Management*, 299-308, Josef Eul Verlag GmbH, Lohmar-Köln (2013)

[8] Nopper, J., Follert, G., and ten Hompel, M., "Gains in the life-cycle of adaptable, self-organized material handling systems," *International Material Handling Research Colloquium (IMHRC) - Proceedings*, 11, 122-132 (2010)

[9] Scholz, D., *Innerbetriebliche Standortplanung - Das Konzept der Slicing Trees bei der Optimierung von Layoutstrukturen*, Gabler Verlag, Springer Fachmedien Wiesbaden GmbH (2010).

[10] Kettner, H., Schmidt, J. and Greim, H.-R., *Leitfaden der systematischen Fabrikplanung*, Hanser Fachbuchverlag (1984).

[11] Armour, G. C. and Buffa, E. S., "A heuristic algorithm and simulation approach to relative location of facilities," *Management Science*, 9, 2, 294-309 (1963).

[12] Bozer, Y. A., Meller, R. D. and Erlebacher, S. J., "An improvement-type layout algorithm for single and multiple floor facilities," *Management Science*, 40, 7, 918-932 (1994).

[13] Grajo, E. S., "Strategic layout planning and simulation for lean manufacturing a layout tutorial", in *Proceedings of the 27th Conference on Winter Simulation*, 510-514 (1995).

[14] Dunker, T., Radons, G. and Westkämper, E., "A coevolutionary algorithm for a facility layout problem," *International Journal of Production Research*, 41, 3479-3500 (2003).

[15] Komarudin and Wong, K. Y., "Applying ant system for solving unequal area facility layout problems," *European Journal of Operational Research*, 202, 3, 730 - 746 (2010).

[16] Becker, T., *Parallels between manufacturing systems in industrial production and metabolic systems in biological cells*, Jacobs University (2012).

[17] Zhan, Y., Feng, Y. and Sapatnekar, S. S., "A fixed-die floorplanning algorithm using an analytical approach," *ASP-DAC '06 Proceedings of the 2006 Asia and South Pacific Design Automation Conference*, 771-776 (2006).

[18] Scheffer, L., Lavagno, L. and Martin, G. (Eds.), *EDA for IC System Design, Verification, and Testing*, Taylor & Francis Group, LLC (2006).

[19] NVIDIA Corporation, Nvidia geforce gtx 590 graphics card datasheet, online, (2011)

[20] Wang, L.-T., Chang, Y.-W. and Cheng, K.-T. T. (Eds.), *Electonic Design Automation: Synthesis, Verification, and Test,* Morgan Kaufmann Publishers (2009).

[21] Lienig, J., *Layoutsynthese elektronischer Schaltungen - grundlegende Algorithmen für die Entwurfsautomatisierung*, Springer, Berlin (2006).

[22] Jansen, D. (Ed.), *The Electronis Design Automation Handbook*. Springer Science+Business Media New York (2003).

[23] Lengauer, T., *Combinatorial Algorithms for Integrated Circuit Layout*, Teubner Verlag (1992).

[24] Kernighan, B. W. and Lin, S., “An efficient heuristic procedure for partitioning graphs,” *Bell System Technical Journal*, 49, 291-307 (1970).

[25] Fiduccia, C. M. and Mattheyses, R. M., “A linear-time heuristic for improving network partitions,” *ACM IEEE Nineteenth Design Automation Conference Proceedings* (1982).

[26] Larsson Träff, J., “Direct graph -partitioning with a kernighan-lin like heuristic,” *Operations Research Letters*, 34, 6 (2006).

[27] Alpert, C. J., Kahng, A. B. and Yao, S.-Z., “Spectral partitioning with multiple eigenvectors,” *Discrete Applied Mathematics*, 90, 1-3, 3-26 (1999).

[28] Spielman, D. A. and Teng, S.-H., “Spectral partitioning works: Planar graphs and finite element meshes”, *Linear Algebra and its Applications*, 421, 2-3, 284-305 (2007).

[29] Diekmann, R., Monien, B. and Preis, R., “Using helpful sets to improve graph bisections,” *Technical Report, Forschergruppe No. 8. AMS*, 57-73 (1995).

[30] Diekmann, R., Lüling, R., Monien, B. and Spräner, C., “Combining helpful sets and parallel simulated annealing for the graph-partitioning problem,” *Parallel Algorithms and Applications*, 8, 61-84 (1996).

[31] Stockmeyer, L., “Optimal orientations of cells in slicing floorplan designs,” *Information and Control*, 57, 2-3, 91-101 (1983).

[32] Kang, S., ”Linear ordering and application to placement,” *Proceedings of the 20th Design Automation Conference*, 457-464 (1983).