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LAYOUT OPTIMIZATION OF A PRODUCTION CELL

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Abstract
An analysis of a product line of small and medium-sized enterprises (SME) shows that products (component parts or assemblies) are quite similar in terms of design and technology, thus clusters of products are formed. For each cluster a production cell can be organized. According to the product line of a company a certain number of individual production cells is organized, while workshop production is retained for the remaining product line.

The paper shows how clusters of products are designed on the basis of a product line data and how an ideal layout optimization is determined on the basis of the intensity of material flow. Layout optimization of a production cell is based on a combination of Schmigalla modified triangular method and the Schwerdfeger circular process. The method was applied on a cluster of 20 orders similar in design and technology that are processed at 10 workplaces. At the end of the article a transition from a theoretical O-cell to a real U-cell is suggested.
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Key Words: Layout Optimization, Manufacturing Cell, Discrete Event Simulation, Clustering, Algorithms

1. INTRODUCTION

Lately, the main objective of optimizing production times and costs is achieved through introduction of lean production methods [1]. The main goal of lean production is to identify, analyse and optimize an internal material flow. For this reason, the traditional workshop layout is because of the long material flow between workplaces, transformed into production cells, which are also the goal of lean production [2], because of short material flows and the possible flexible work in the cell. Many processes have been proposed for the formation of production cells [3-7]. In 2013, Askin [8] made an overview of concepts concerning clustering of component parts or assemblies for a cell.

In 2013, Ficko and Palcic [9] described an application of genetic algorithms for solving the layout planning problem using the modified triangle method. In 2016, Yilmaz et al. [10] also considered worker resource and flow times simultaneously.

Promising results obtained by SOM neural networks encouraged us to clustering on the basis of SOM [11] taking 58 different attributes for clustering into account. This resulted in optimized production cells [12], whose machines were manually placed in the cell for simplicity reasons. A force-directed layout optimisation method was introduced by [13] and integrates random permutations using simulated annealing to avoid local minima.

In the paper [14] an alternative solution for production management was proposed with a simulation modelling in order to improve machinery production process in job shop with alternative strategies based on basic operations management principles.

It becomes evident from literature review [15-18] that many different methods can be applied for layout optimization in a production cell. In addition to before mentioned optimization methods a method of discrete event simulation [19-21] is more and more frequently used lately. Centobelli et al. [22] represented the proposal of a layout reconfiguration supported by a simulation model in order to reduce the production lead times, assessed by the Digital Factory implementation approach. In this case, real production

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systems and processes are transferred to a digital environment; a digital twin is modelled and erected. The results of simulation in the digital twin provide evaluated information that can be used for fast, reliable and reasonable decisions in early stages of production planning, optimization phase or continuous improvements [23, 24]. The main advantage of using discrete event simulation is that only real data are used, no real materials, energy and other resources are used [20]. Thus, different variants of production sequences and production plans can be evaluated in advance in order to find an optimal or sub-optimal solution.

This is why the algorithm for fine (detailed) layout planning inside cells was upgraded with simulation model which gave us evaluated results in order to find an optimal layout of a production cell. In production four basic production principles are known [25]: on-site, job-shop, flow and cellular production principle (see Fig. 1).

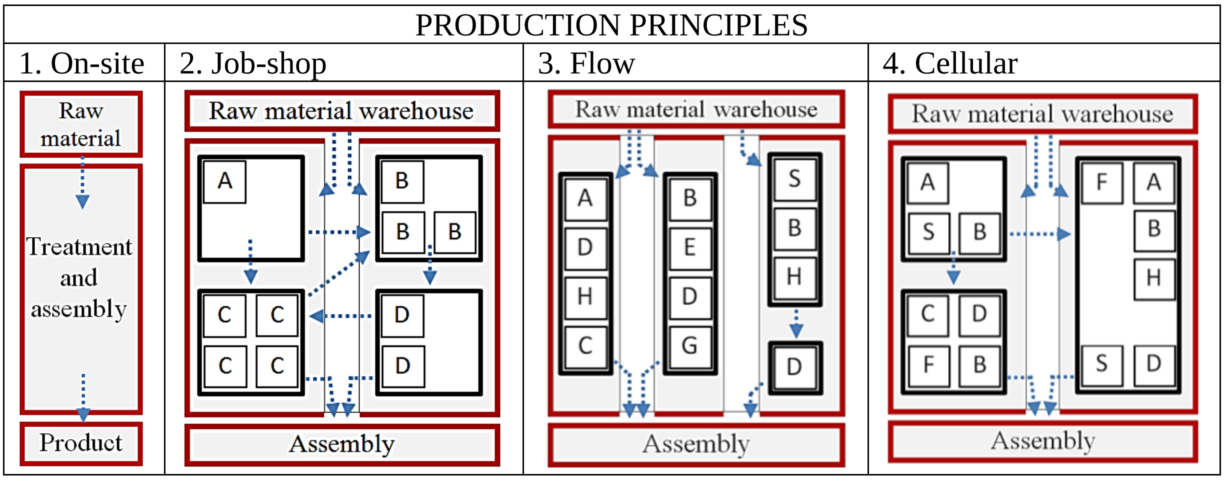

Figure 1: Production principles [25].

The principle of on-site production is normally used when the product is very small and requires many different assembly operations. It is carried out on a working table or when machining and assembly is carried out in a certain place, because the components of the final product are too large, too heavy or unstable for transport (construction of buildings, ships and aircrafts).

In a job-shop production manufacturing operations or machines (sawing, turning, hardening) are spatially segregated in different job-shops. A workpiece is transported from one job-shop to another which results in long lead times of operation and consequently long lead times of orders. Nowadays, the job-shop production principle is used only for small batches and for production of prototypes.

In flow production a production line is formed for each component part or assembly. Each production line is composed of all machines and devices needed for production of component parts or assembly in the sequence of a one-way road.

Cellular production is characterized by combining component parts and/or assemblies depending on physical or technical production similarities of clusters of component parts and assemblies. A production cell represents a working system that is not focused on tasks but on products. The necessary machines and equipment are integrated in a single production cell needed for completion of a cluster of component parts and assemblies. The result of a cellular production is a production or assembly cell, in which the complete process of component parts or assembly of the final products is made. All team members need to have the same qualifications, because they have to be able to carry out all the necessary activities in the cell. In addition to professional competencies (knowledge management, methods and procedures) they need to handle social skills (communication and co-operation with members of the team, conflict resolution).

Team members assume responsibility for planning, implementation of processing, quality control of products and maintenance of the production cell.

Fig. 2 shows an organizational structure of a production cell.

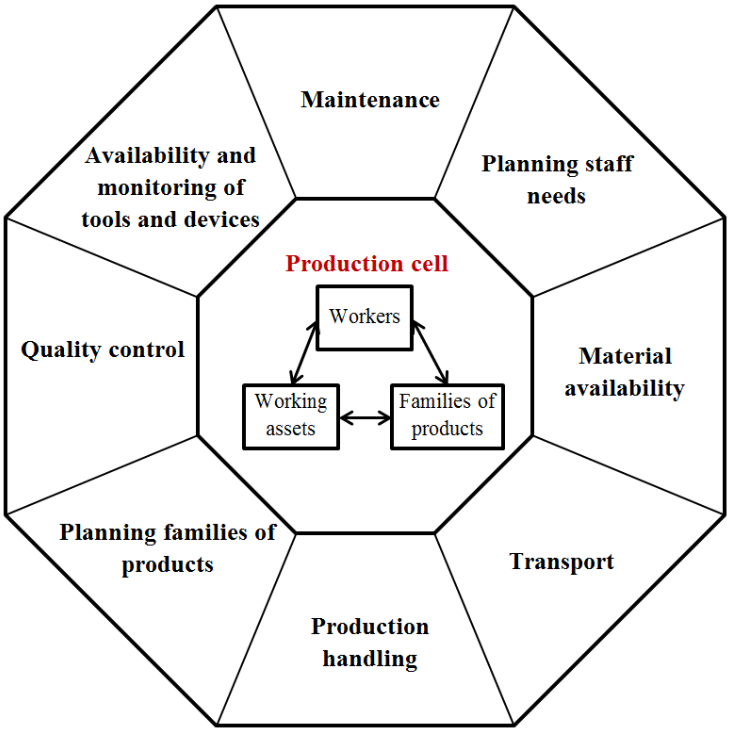

Figure 2: Organizational structure of a production cell.

Sankey's chart [26] or even more often clustering [27, 28] is used to define production cells.

Advantages of cellular production are as follows:

- short lead times of orders (due to shorter transport routes),
- low storage costs (due to lower intermediate storage conditions),
- production process is more transparent and better organized,
- team members are more motivated,
- team members are trained to assume various tasks in the team,
- team members are responsible for meeting requirements relating to quality and terms,
- team members define work distribution and working pace.

Disadvantages of cellular production are as follows:

- it requires a new type of co-workers, the so-called generalists,
- it requires high qualification of the team members (for all areas of work),
- utilization of machines is lower than in a workshop production.

Table I shows appropriateness of using the production principles.

Table I: The appropriateness of using the production principles.

Features / Principle	**Flexibility**	**Material flow**	**Suitable for**	**Type of production**
On-site production	Partial	No flow	Local bonded facilities	Individual production
Job-shop production	Excellent	No flow	Fluctuating orders	Individual production
Flow production	Non	Flow	Large series	Mass production
Cellular production	Partial	Partial flow	Families of parts	Medium and large series production

2. PRODUCT CLUSTERS AND FINE LAYOUT PLANNING IN CELLS

An important task of optimizing cellular production is planning of product clusters of component parts or assemblies (hereinafter referred to as products) and fine layout planning in manufacturing cells.

2.1 The formation of product clusters

A simple process of forming product clusters is based on a matrix of product clusters of a company, which covers all company products and all operations that need to be carried out on the products.

By analysing the matrix, products sharing the same or similar operations or workplaces are grouped in one product cluster. Table II shows an example of two product clusters FP1 and FP2.

Table II: Matrix of product clusters.

ID of product	Workplaces / Family of products	Drilling	Milling	Turning	Grinding	Hardening	Washing	Lacquering	Pre-assembly 1	Pre-assembly 2	Assembly 1	Assembly 2
P1	FP 1	X		X	X	X		X	X			
P3		X		X	X	X			X			
P6		X		X		X		X	X			
P4				X	X				X			
P8		X		X		X			X			
P9	FP 2		X	X			X	X		X		X
P5			X				X	X		X		X
P2			X	X			X			X		X
P7			X				X			X		X

The presented process of forming product clusters is suitable for a production of a small number of products while it loses transparency in case of a large number of products. A weakness of this matrix is that it does not take the criterion of products similarity into account.

A suitable procedure for determining families of a larger number of products is carried out in two steps:

1st step: Designing a production flow scheme which shows significant differences in manufacturing processes.

2nd step: Product distribution in clusters according to their similarity (material, weight, volume).

Fig. 3 shows an example of product clustering based on similarity.

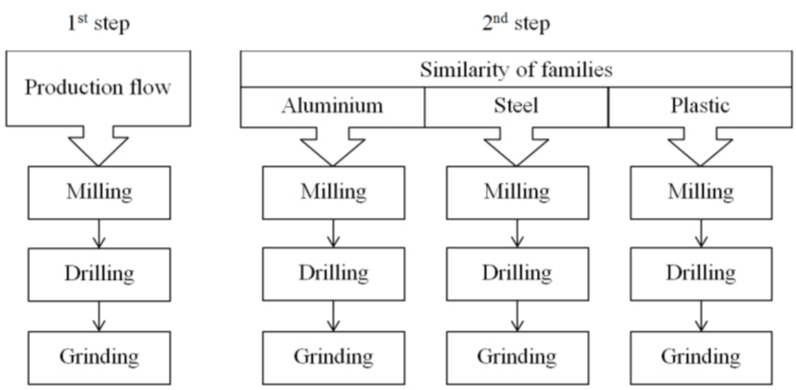

Figure 3: Formation of product clusters based on similarity.

Product clusters can also be formed on the basis of self-organising neural networks [11] which are the basis for cell formation.

2.2 Sub-optimal fine layout of machines in a production cell

After the families of products and the production cells have been formed, an optimal arrangement of machines in a cell needs to be determined for each cell.

To show the intensity of a material flow among machines in a production cell, the material flow matrix or a transport matrix is often used. An example is shown in Table III.

Table III: Material flow matrix of a production cell.

To / From	Machine 1	Machine 2	Machine 3	Machine 4	Machine 5	Machine 6
Machine 1		900	300		500	200
Machine 2			400		100	400
Machine 3				200	200	300
Machine 4					200	
Machine 5						1000
Machine 6						

The material flow matrix of a production cell represents the basis for sizing the required number of transport means and fine layout of machinery / equipment in a production cell.

The article [12] presents cell building and a rough layout of machines in a cell based on the Schmigalla modified triangular method (manual arrangement by operator). This rough arrangement of the operator will now be upgraded with a suboptimal fine layout of machines in a cell by using Schwerdfeger circular simulation process.

2.3 Schmigalla modified triangular method

The Schmigalla modified triangular method [29] is a heuristic method for arrangement of machines. This is a method, in which machines are arranged "one after another" in a triangle intersection (see Fig. 4).

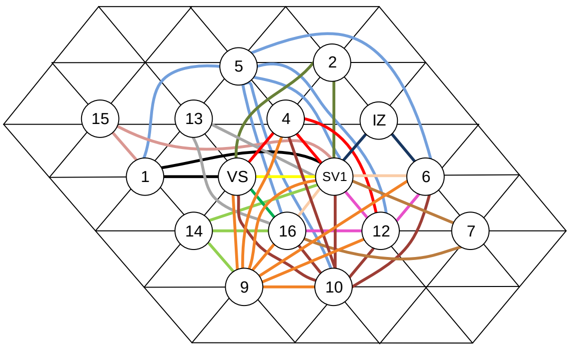

Figure 4: An example of Schmigalla modified triangular method.

Based on the steps of the Schmigalla modified triangular method, a rough layout is obtained:

1st step: Arrangement of first two machines, between which there is maximal intensity of material flow.

2nd step: Determination of the machine having a maximum sum of intensity of the material flow with the previously arranged machines.

3rd step: Repeating the second step until the last machine in the cell is arranged.

Software package VisTABLE 2.3.005, into which technology, a quantity of manufactured products to be produced in a cell, and the type and cost of transport is used to build a 2D model of a virtual cell with a presentation of the material flow, its intensity and transport costs. In the background a 3D model of a virtual cell is made which serves mainly to present the results.

Based on the integrated Schmigalla modified triangular method the machines are arranged in a sequence depending on the material flow intensity.

2.4 Schwerdfeger circular method

The Schwerdfeger circular method contains the following steps:

1st step: Machines needed for the processing of a certain product cluster are arranged in a circle. Connections of material flows between machines are indicated with connecting arrows.

2nd step: Material flow intensity between the machines is indicated with the width of the arrow.

3rd step: By moving the machines on the circle we are gradually looking for a fine layout, in which the machines are intensely connected in terms of material on the circumference of the circle and at a minimum distance among each other. The material-intense connecting arrows will not project over the circle but will be tangential to the circumference of the circle.

When arranging machines according to a circular process, a single circle (see Fig. 5) needs to be first defined with the data:

- number of machines in a cell n,
- length of the secants $S(1) = 1$ and
- angle α, $\alpha = \frac{360}{n}$.

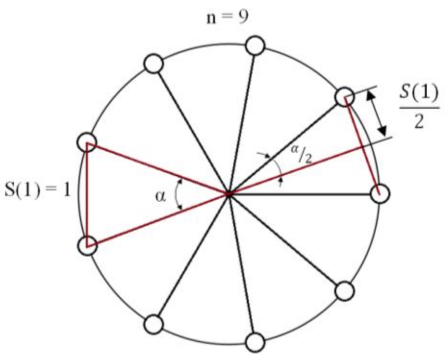

Figure 5: Single circle.

Once the single circle is determined, the following can be determined (see Fig. 6):

- circle radius r,
- length of path $S(2)$, $S(3)$,…,$S(n)$ and
- transport costs TC.

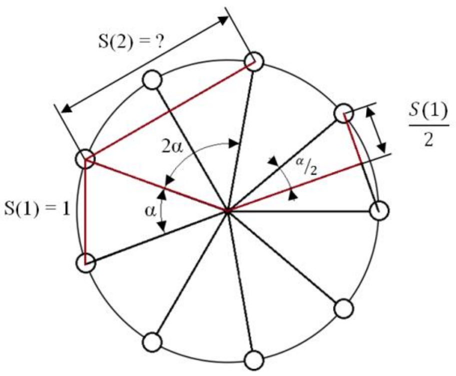

Figure 6: Determination of r, $S(n)$ and TC.

1. Radius of circle r

Wherein (see Fig. 6):

$$sin\frac{\alpha}{2} = \frac{\frac{S(1)}{2}}{r} \tag{1}$$

the radius r of circle is:

$$r = \frac{\frac{S(1)}{2}}{sin\frac{\alpha}{2}} \tag{2}$$

2. Length of path $S(2)$

Wherein (see Fig. 6):

$$sin\frac{2\alpha}{2} = \frac{\frac{S(2)}{2}}{r} \tag{3}$$

the length of path $S(2)$ is:

$$\frac{S(2)}{2} = r\sin\left(\frac{2\alpha}{2}\right) \tag{4}$$

$$S(2) = 2\frac{\frac{S(1)}{2}}{sin\frac{\alpha}{2}}\sin\left(\frac{2\alpha}{2}\right) \tag{5}$$

$$S(2) = \frac{S(1)}{sin\frac{\alpha}{2}}\sin\left(\frac{2\alpha}{2}\right) \tag{6}$$

3. Length of path $S(n)$

It is in general valid:

$$S(n) = \frac{S(1)}{sin\frac{\alpha}{2}}\sin\left(\frac{n\alpha}{2}\right) \tag{7}$$

4. Total transport costs

$$TC = \sum_{i=1}^{n}\sum_{j=1}^{n} T_{ij}S_{ij}s_{ij} \tag{8}$$

wherein:

TC – total transport costs,
T_{ij} – intensity of a material flow from a machine i to a machine j,
S_{ij} – length of transport path from a machine i to a machine j,
s_{ij} – cost per unit of path from a machine i to a machine j,
n – number of all machines.

2.5 Simulation model for fine layout of machines

Looking for an optimal fine layout of machines is known as an NP-hard optimization problem [16, 17, 30]. Therefore, application of metaheuristics is justified when looking for optimal or near optimal solutions in a reasonable time [18]. Result of a heuristics is usually called a near optimal solution because we have no proof of its optimality. As it is usually the best solution known we will for simplicity call it optimal solution although it should be called “the best known near optimal solution”. The discrete event simulation will be used, which allows us to do “what-if” scenarios and usage of algorithms.

The software package Tecnomatix Plant Simulation was used for model building and simulation. This is the leading software solution to modelling and simulation based on discrete event theory and is object-oriented.

The goal of the simulation is to determine the optimal arrangement of machines in a production cell. Simulation is used to evaluate, in which order machines have to be arranged in the cell in order to obtain the lowest transport costs of all orders in a selected time interval.

The production cell will be evaluated in a digital twin or a simulation model based on the actual production system (see Fig. 7).

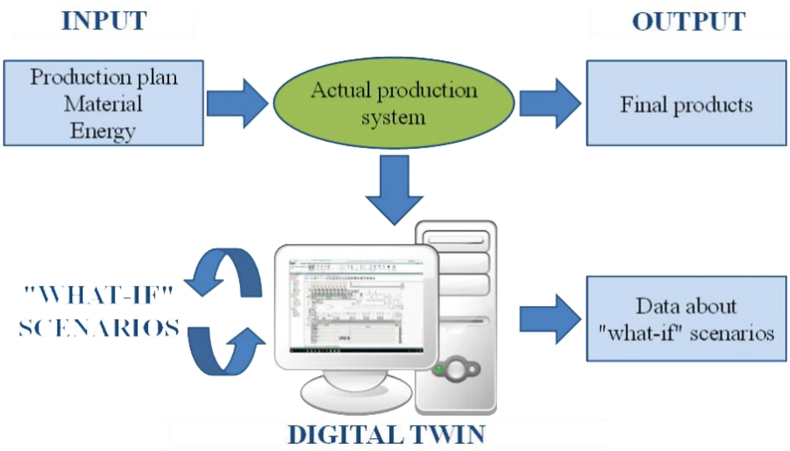

Figure 7: Basic principle of a digital twin [20].

A model for an observed production cell is designed to make use of actual production input data. The model will describe all the essential characteristics of the production system. Information from the digital twin (simulation) will be used to evaluate the optimal or sub-optimal fine layout of machines in a production cell.

Based on the assumptions of the digital production process and the characteristics of the actual production process, a logical scheme of a production cell will be designed (see Fig. 8).

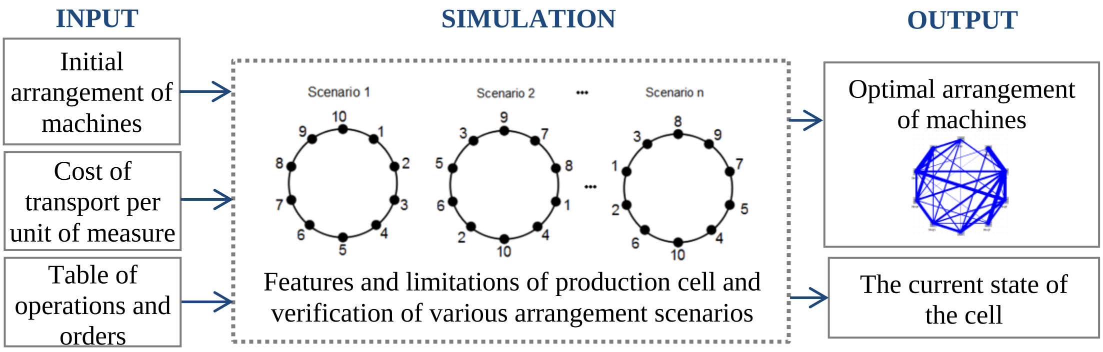

Figure 8: Logical scheme of the production cell.

The simulation model was designed on the basis of the input data (technology, amount, material flow, costs and type of transport). The simulation model represents the current state of the production cell and includes all its properties in a selected point of time. Every workplace represents one machine which includes a buffer and a place where operation is carried out.

The output data of the simulation will include:

- material flow intensity between machines,
- transport costs and
- Sankey chart.

The Schwerdfeger circular process of machine arrangement in the cell presents an alternative to the Schmigalla modified triangular method [29].

Researchers of the laboratories LAPS and LASIM, University of Ljubljana, Faculty of Mechanical Engineering, decided to compare fine cell layouts of the Schmigalla modified triangular method and the Schwerdtfeger circular process in the following sequence:

1st step: Search for sub-optimal machine fine layout in the cell with the software package VisTABLE 2.1.005 based on the embedded algorithm of the Schmigalla modified triangular method.

2nd step: Simulation for finding the optimal machine fine layout in the cell with the help of the program Siemens Plant Simulation. Simulation results will be transferred to the software package VisTABLE for visualisation of the optimal machine fine layout in the cell.

3rd step: Comparison of the obtained results of the fine layout in the cell (determining savings on the internal transport cost).

3. AN EXAMPLE OF FINE MACHINE LAYOUT IN A CELL

According to the described methodology we performed optimization of arrangement of 10 machines of the observed cell for the given example of production. In a selected time interval 20 orders have to be manufactured in cell C1. Table IV shows the needed operations and the necessary quantities of products which are processed in cell C1.

Table IV: Overview of orders and annual volumes of production cells C1.

Order	Workplace Amount [pieces/ year]	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10
O1	100	100	100		100	100				100	
O2	350			350			350				350
O3	220		220		220	220			220		
O18	210					210		210			
O19	160			160					160		160
O20	5				5						

3.1 Suboptimal fine layout based on the Schmigalla modified triangular method

Data about circle radius r = 10 m, the number of machines in cell C1 n = 10 machines, material flow intensity T_{ij}, transport cost per unit between machines s_{ij}, which is 1 €/m and length of secants S_{ij} were inserted into the VisTable program. Sub-optimal arrangement of machines was observed in cell C1 as shown in Fig. 9.

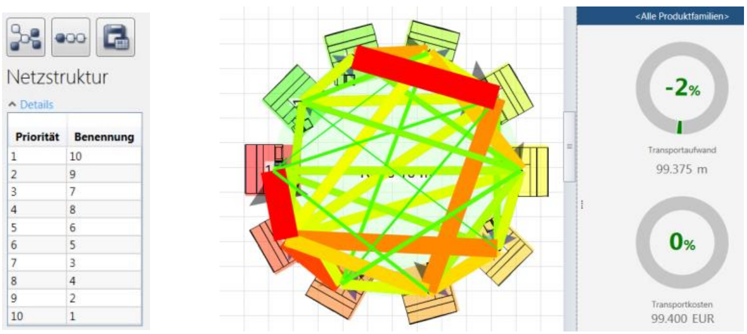

Figure 9: A sub-optimal fine layout with the Schmigalla modified triangular method built into the program VisTable.

Sub-optimal fine layout placement in the cell with Schmigalla modified triangular method which is built into the VisTable program shows the order of machines: M10, M9, M7, M8, M6, M5, M3, M4, M2, M1, in which the total intensity of material flow between machines is 99375 m/year, which amounts to 99400 €/year of total transport costs TC.

The machine in cell C1 with the highest priority is coloured red and the one with the lowest is coloured green. The strongest material flow between the machines is illustrated with a wide red line and the weakest material flow with thin green line as shown in Fig. 11.

Fig. 10 shows the intensity of material flow in relation to the transport distance after using the Schmigalla modified triangular method.

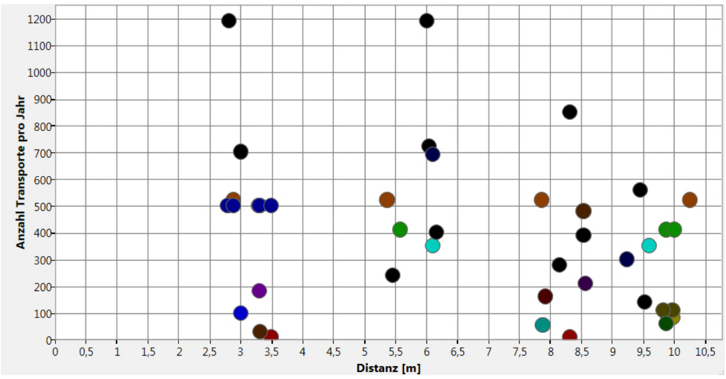

Figure 10: Intensity of material flow in relation to the distance by the sub-optimal fine layout.

Fig. 10 shows the relation of the number of transports per year and the transported distance. Most notable are the 1,200 transports which are performed at a distance of 2.8 m and 6 m (which is also indicated with a red link in Fig. 11 between machines 10 and 9 and machines 2 and 3). This represents the maximum number of transports per year in our case. Ideally, a higher number of transports should be carried out at shorter distances, so all the data in the graph should be at the shortest possible distance.

3.2 Simulation of the optimal fine layout

The simulation model was built in the Plant Simulation software package. The simple logical dependences of the production processes in the model are denoted by standard software package objects, and the complex logical dependences are denoted with methods or libraries in the programming language SimTalk [31].

The model is designed to calculate material flow of all orders for the initial arrangement of machines on the circumference in cell C1. After the information of the material flow intensity between machines T_{ij} and the length of the route S_{ij} for the initial arrangement of machines is added in the simulation, it starts to seek for a better arrangement of machines on the circumference by using a genetic algorithm. The genetic algorithm (number of generations: 30; size of generation: 100) is used to change the arrangement on the circumference and to calculate the total material flow intensity and total transportation costs of orders *TC* for every combination. This process is carried out until the genetic algorithm is no longer able to find a better solution and thus finds the optimal solution.

The purpose of the simulation is to evaluate the impact of various arrangements of machines that genetic algorithm propose on the total material flow intensity of orders between the machines.

The machines were distributed evenly across the circumference, wherein the distance between adjacent machines is always the same. All distances or path lengths between the machines were calculated using Eq. (7).

The total transport cost *TC* between machines was calculated with Eq. (8).

Based on the simulation we got the optimal machine fine layout in production cell C1. The optimal machine order is: M3, M8, M6, M9, M10, M7, M5, M4, M1, M2, in which the total intensity of material flow between machines is 91,889 m/year and total transport costs 91,828 €/year.

Results obtained with the Plant Simulation program simulating the optimal arrangement of machines in production cell C1 is shown by means of the software package VisTable in Fig. 11.

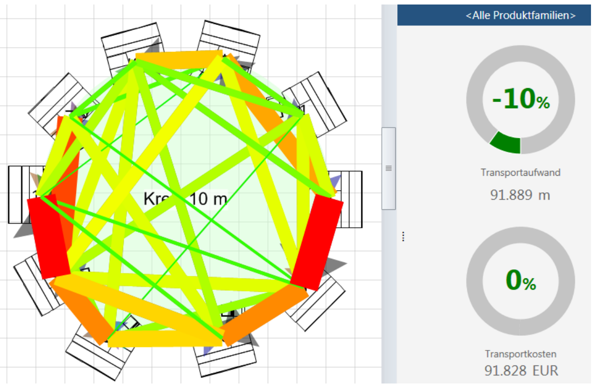

Figure 11: Display of optimal arrangement of machines in cell C1.

Fig. 12 show the intensity of material flow in relation to the transport distance for the optimal machine fine layout obtained with the simulation and support of the program VisTable.

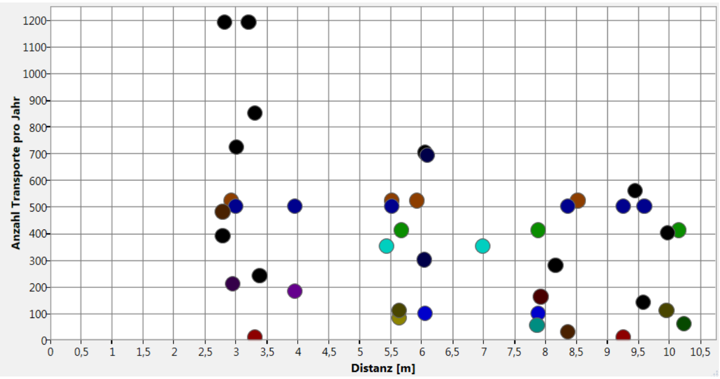

Figure 12: The intensity of material flow in relation to the distance of the optimal arrangement after simulation and support of the program VisTable.

As seen from Fig. 12 the 1,200 transports are performed at a distance of 2.8 m and at 3.2 m instead of 6 m in comparison with the Fig. 11. Between 9 and 10.5 m are in Fig. 13 eleven relations, in Fig. 16 only nine. So the goal, to lower the distance of big numbers of transports was achieved.

3.3 Results of fine layout

Savings of total transport cost between the sub-optimal and optimal arrangement amount are 99,400€/year to 91,828€/year, so the difference is 7,572 €/year.

In reality, it is not possible to design a cell in the form of a circle but is usually U-shaped. This deviates the result slightly away from the optimum and the following arrangement in the cell is obtained: M7, M10, M9, M6, M8, M3, M2, M4, M5, M1 as shown in Fig. 13. When switching from the circular fine layout to the U-shaped fine layout, the total transport costs rise from 91,828 €/year to 96,730 €/year. This means that the arrangement in a U-shaped cell is worse than the optimal arrangement for 91,828 – 96,730 = – 4,902 €/year. An arrangement in a U-cell is shown in Fig. 13.

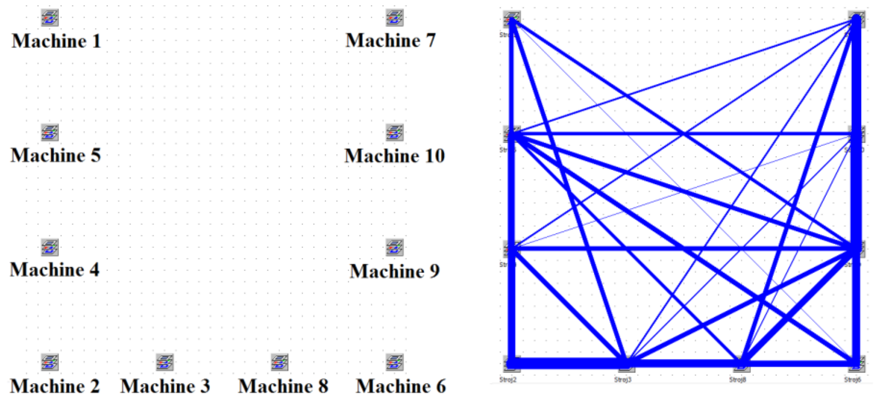

Figure 13: Optimal arrangement of machines in a U-cell.

Fig. 14 shows the layout of machines, material flow intensity in relation to the transport distance and the transport cost when switching from O-cell to U-shaped cell, were we retain the 10 m radius for comparison between O and U shapes. If we would narrow this radius the results would be even better. Fig. 14 b shows the material in a U-shaped cell.

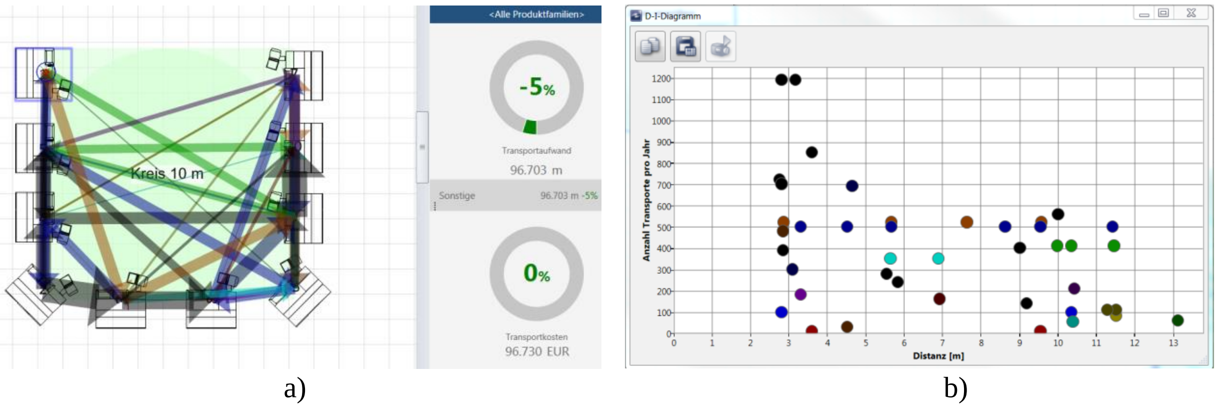

Figure 14: a) Display of optimal arrangement of machines and material flow in U-shaped cell C1 after simulation in the program VisTable;
b) Material flow intensity in relation to the distance in a U-shaped cell.

As evident from Fig. 14 a, the fine layout in a U-shaped cell is by 5 % worse than the optimal fine layout of an O-shaped cell. Fig. 14 b shows that the largest intensities of 1,200 transports per year are at the shortest possible distance. The same applies for all intensities over 600 annual transports.

4. CONCLUSION

Today, customers require that the company delivers right products to the right place, in proper quantity, proper quality, at the right time and at proper price.

If small or medium-sized enterprises want to meet customers' requirements, they have to switch from the workshop production principle to the flow production principle if possible, or to a combination of workshop-cellular production. In the workshop production principle technologically and dimensionally dissimilar products are produced. In the cellular production principle technologically and dimensionally similar products are produced. Team members of a production cell assume responsibility for planning, execution of processing, quality control of products and maintenance of production cells.

Our approach with combining digital twin and genetic algorithm showed that this is an effective way to evaluate optimal layout of production cell. We can also quickly and easily change the process parameters and promptly see which implications these parameters have on the production process inside production cell in advance. This is particularly important due to the fact that a production call can be very flexible, and by using the what-if scenarios in advance we can remove all costs, that would appear if no evaluation would be carried out.

We used two different shapes of production cells – we started with theoretical production cell in the form of the letter O and continued with realistic production cell in the form of the letter U. As expected optimal O-shaped production cell gave us 5 % better results – shorter flow times and less transport costs, than U-shaped production cell.

We need to acknowledge that production cell in reality is designed in the form of the letter U. Our approach showed that we can shorten flow times of the products, lower intermediate product storage, and generally speaking obtained less wastes, all of which lead to lean production.

Further research will be focused on computer-assisted determination of product families according to similarity, design of the fine layout of production cells and methods for optimization of the internal transport between the machines in a production cell.

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