Optimization of a furniture factory layout

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Abstract. This paper deals with the problem of optimizing a factory floor layout in a Slovenian furniture factory. First, the current state of the manufacturing system is analyzed by constructing a discrete event simulation (DES) model that reflects the manufacturing processes. The company produces over 10,000 different products, and their manufacturing processes include approximately 30,000 subprocesses. Therefore, manually constructing a model to include every subprocess is not feasible. To overcome this problem, a method for automated model construction was developed to construct a DES model based on a selection of manufacturing orders and relevant subprocesses. The obtained simulation model provided insight into the manufacturing processes and enable easy modification of model parameters for optimizing the manufacturing processes.

Finally, the optimization problem was solved: the total distance the products had to traverse between machines was minimized by devising an optimal machine layout. With the introduction of certain simplifications, the problem was best described as a quadratic assignment problem. A novel heuristic method based on force-directed graph drawing algorithms was developed. Optimizing the floor layout resulted in a significant reduction of total travel distance for the products.

Keywords: discrete event simulation, automated model construction, factory layout, heuristic optimization, quadratic assignment problem, force-directed graph drawing algorithm

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1. Introduction

Optimization of manufacturing processes is one of the key goals in every successful manufacturing company. If a process is simple enough, it can be adequately represented by an exact mathematical model and optimized effectively using an analytical mathematical algorithm. In the real world though, the processes are usually too complex to be tackled with this approach and a good alternative is to construct a simulation model by applying, for instance,

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the discrete event simulation (DES) methodology to understand and analyze factory floor processes.

The direct approach is to build every segment of the model by hand. However if the manufacturing process is very complex or numerous variations of the model are to be built, the modelling can be very time consuming and the resulting model may require extensive computer resources. Automated model building methods can significantly speed up the modelling, but require all model construction parameters in the form of structured files. Automated model building is also an important step in the development of model optimization algorithms.

The primary focus of the project is to investigate how a machine layout on a factory floor affects the efficiency of manufacturing processes. Subsequently, the layout is optimized according to selected criteria. This paper focuses on optimizing the total distance manufactured products are required to travel between machines, which is carried out by optimizing the floor layout, i.e. repositioning the machines on the floor.

1.1. Problem situation

The furniture company uses approximately 140 machines and produces over 30,000 different products and intermediate products. Every product has an associated 'technical procedure', i.e. a sequence of prescribed tasks on one or more machines. For each product and task, there is a list of suitable machines and estimated preparation and operation times. Complex products are manufactured by combining smaller semi-finished products as prescribed by a bill of materials (*BOM*). After a machine task has finished, the entire series of products is carted to the next designated machine location. The list of all final products to be manufactured comes from a client's order. Typically, there are multiple concurrent active factory orders.

Due to the large range of different products and variations in the content of manufacturing orders, developing a static model covering all possible product development processes is not feasible. Instead, the model is built automatically from a model template, a database of technical procedures and a database of currently open orders. During the simulation, technical procedures and BOMs are read dynamically from input data.

1.2. Previous research (review of literature)

Simulation is commonly used for evaluating scenarios [1], [2] and [3]. However, the models developed implementing a visual interactive modelling method (VIM) are usually constructed manually by careful analyzing the real-life system and communication amongst process owners. Automated model development is more common with methods that enable easier and more standardized formal description of models, e.g. Petri nets [4] and [5]. Automated model construction and adaptation can significantly facilitate the development of complex system models [6] and [7] and the generation of simulation scenarios.

There are several papers dealing with the topic of factory layout optimization. Paper [8] asserts that multiproduct enterprises require a new generation of flexible, modular and reconfigurable factory layouts. Evolutionary optimization methods are often proposed due to problem complexity [9]. The layout optimization problem is identified as a difficult combinatorial optimization problem and the simulated annealing (SA) meta-heuristic resolution approach is a proposed solution [10]. A novel particle swarm optimization method is given in [11] enabling intelligent designing of an unconstrained layout for flexible manufacturing systems.

Factory layout design and optimization is further discussed in [12], [13] and [14]. The authors in [12] propose a new model for facility layout designs in order to optimize material handling costs. Genetic algorithm-based solutions are proposed in [13] and [14] that respond to the changes to the product design, mix and volume in a continuously evolving work environment.

The quadratic assignment problem has received a lot of attention in the last several decades. It was first formally described in [15] and proven to be NP-hard in [16]. Several open source QAP heuristic method implementations are available on the QAPLIB website (http://www.opt.math.tu-graz.ac.at/qaplib/codes.html).

Force-directed graph drawing methods (also called spring embedders) are one of the most commonly used methods to represent graphs visually. For a review of the literature, see [17] and [18], and their references.

1.3. Project plan and status

The first goal was to develop a manufacturing process simulation model that would reflect the existing situation in the company. The model was verified by feeding it with test data and historical order data prepared by the company planners. This phase of the project involved developing an automated model-building algorithm. The discrete event simulation model was built using Anylogic software (http://www.anylogic.com), which saves the models as XML files. Outcome of this phase of the project was an application in Java that constructs the model by modifying an XML file based on a template model.

The goal of the next phase of the project was to find a better floor layout, i.e. optimal machine placement. Layout improvements can be achieved by applying heuristic optimization methods, and expertise from company planners and other employees. Currently, the focus has been placed on optimizing the total path distance the products traverse on the factory floor. The problem can be presented as a quadratic assignment problem (QAP) and different heuristic algorithms for finding suboptimal solutions already exist.

An alternative to the standard QAP algorithms is a promising application inspired by force-directed graph drawing algorithms. Machines are represented as nodes in a graph and overall direct transactions between the machines (amount of products) are represented as weighted edges. Edges represent attractive forces between the nodes. All nodes are also assigned repelling forces given that the corresponding machine requires a certain amount of available factory floor area. The nodes are moved according to the set forces and the system gradually stabilizes in a configuration with a local minimum of the overall system energy. The first test showed that the method produces good results, comparable to the established QAP heuristics.

2. Model description

In this section, a description of the machines, procedures and processes in the company is provided in more detail. Subsequently, the simulation model and the key methodologies used are also presented.

The company floor layout comprises approximately 140 machines (workstations). Each machine operates independently and assumes a certain amount of factory floor space. A network of routes is defined in the layout around the machines. The routes enable the carting of products between the machines.

Each machine can perform specific operations. Prior to an operation, the machine has to be set up to perform the prescribed tasks. Both the setup and operation take a specific amount of time.

Every machine is described by the following pseudo-algorithm:

(1) If an input pallet is not empty, pick a product from the list according to the given *priority* parameters; else wait.
(2) Set up the machine.
(3) Apply the operations for the entire product series (products then wait on the output pallets).
(4) Pick the next least loaded machine for the next operation.
(5) A product series is moved onto the next machine.
(6) Go to (1).

An *order* is a list of products that is to be manufactured. Usually there are several simultaneously open (active) orders in production. An order is a considerably smaller number of different products than the 30,000 already mentioned. To simulate manufacturing processes over a specific time interval, only products specified in currently open orders are considered. An order is described as a list of products (catalogue numbers). Every product from the list is assigned a name, quantity, the earliest start time (EST), priority parameter and volume. An example of an order for three products is shown in Table 1.

Catalogue no.	Name	Quantity	EST [date]	Priority	Volume [m^3]
0301050 000102	Frame Autumn 2XR	124	7. 1. 14	11	0.00304
7001 62267 61M	Strip side	81	7. 1. 14	12	0.000647
7001 62842 61M	Strip pine	68	7. 1. 14	14	0.000904

Table 1: *Three products from an order and their properties.*

Each product has a specific technical procedure. Every operation refers to a group of equivalent machines, a preferred machine, setup time and time per item. Products that are more complex also have a bill of materials, a list of required semi-finished products or materials that are incorporated at a specific operation in a specific quantity.

As all technical procedures are stored for every product, additional characteristics for the machines need not be specified. Hence, every machine in Anylogic is represented by the same instance of a generic machine. The machines are differentiated solely by their names and layout placements.

All the mentioned input data (orders, technical procedures, BOMs) and list of all equivalent machine groups were obtained from SQL database queries, generated by Preactor software. The queries were saved as views and specially prepared for the simulation model.

During simulation, various statistical data were logged. Once the simulation finished, all data were stored in an Excel file. Different flow types comprising the number of products, number of used carts, total product volume and total cart distances between all possible pairs of machines were measured. Utilization, overall setup time, product flow and volume, and queue lengths were monitored for each machine. Furthermore, the starting and ending times for each product series were measured, and machine sequences chosen during simulation were stored. Cart flows and cart routes were also recorded.

3. Optimization methodology

Output data derived from simulation of the manufacturing processes provided product flows (product volumes) for every machine pair independently on the factory floor layout. This section describes the problem of determining factory floor that minimize total transport distances of the products during production.

It relates directly to measured product flows between the machines and machine positions.

The factory floor is described as a region Ω in the plane $\mathbb{R}^2$. The problem was simplified by restricting Ω to a rectangular shape,

$$\boldsymbol{\Omega} = \{(\boldsymbol{x}, \boldsymbol{y}) \in \mathbb{R}^2 \colon \boldsymbol{x_{min}} \leq \boldsymbol{x} \leq \boldsymbol{x_{max}}, \boldsymbol{y_{min}} \leq \boldsymbol{y} \leq \boldsymbol{y_{max}}\}, \tag{1}$$

where $x_{min}, x_{max}, y_{min}, y_{max}$ represent boundaries of the rectangular factory floor.

The machines are denote by m_i, $i = 1,2, \dots, N$. A machine position m_i is described by

$$p_i = \{(x_i, y_i) \in \mathbb{R}^2\}. \tag{2}$$

Each machine needs certain amount of space conveniently described by a metric rectangular-like ball $B_{r_i}(p_i)$ with radius r_i and center p_i in ∞-norm L_∞,

$$B_{r_i}(p_i) = \{(x, y) \in \mathbb{R}^2 \colon d_\infty((x, y), p_i) = max\{|x - x_i|, |y - y_i|\} < r_i\}. \tag{3}$$

For every pair of machines m_i and m_j, $i, j = 1,2, \dots, N$, the sought product flow $f_{ij} \geq 0$ is obtained from simulation of the manufacturing processes.

The distance $d(m_i, m_j)$ between a machine pair m_i and m_j is defined as the shortest path between the machines in a predefined network of routes.

The optimization problem involving minimizing the total distance is described as

$$min_{\{p_1, p_2, \dots, p_N\}} \left(\sum_{\substack{i,j=1 \\ i \neq j}}^{N} f_{ij} \cdot d(m_i, m_j) \right), \tag{4}$$

where positions p_i must satisfy the conditions

$$B_{r_i}(p_i) \cap B_{r_j}(p_j) = \emptyset \tag{5}$$

for every $i \neq j$ and

$$B_{r_i}(p_i) \subset \Omega \tag{6}$$

for every $i = 1,2, \dots, N$. The condition (5) states that machine regions must not intersect each other and the condition (6) implies that every machine must lie entirely with the factory floor area.

Each machine layout requires defining a suitable network of routes. To simplify the tedious problem of defining the network from the machine positions, the presumed distance between the machines takes the form of the well-known Manhattan distance,

$$d_M(m_i, m_j) = |x_i - x_j| + |y_i - y_j|. \tag{7}$$

As the original routes are based on rectangular grids, differences in path lengths are small if the functional d_M is used instead of d.

If the presumption is made that all machines need the same amount of space (all radii r_i are the same) the positions p_i can be restricted to discrete points on a predefined grid. Hence, the problem simplifies to well-known quadratic assignment problem (QAP), where the optimization goal is to find the best possible permutation of machines on the grid.

3.1. Force-directed graph drawing algorithm

This section presents a novel heuristic optimization algorithm for assigning positions p_i to machines m_i. The algorithm is based on force-directed graph drawing methods. The positioning of machines in the system is based on applied forces, which converges to a configuration possessing a local minimum of the overall energy.

Each machine is presented as a node on a plane. For every pair of nodes n_i, n_j the corresponding repulsive force F_{ij} is defined.

$$F_{ij} = H_{ij}\left(||p_j - p_i||_\infty\right) \cdot \frac{p_j - p_i}{||p_j - p_i||_\infty}, \tag{8}$$

where H_{ij} is a positive monotonically decreasing function. Typically, H_{ij} is defined as $H_{ij}(r) = r^{-2}$. Repulsive forces repel nodes away from each other to obtain required space between the machines.

For each node pair n_i, n_j a weighted edge e_{ij} with a weight f_{ij} is defined. Attractive forces between the nodes are defined as

$$G_{ij} = -f_{ij} \cdot I_{ij}\left(||p_j - p_i||_1\right) \cdot \frac{p_j - p_i}{||p_j - p_i||_1}, \tag{9}$$

where I_{ij} is a positive monotonically increasing function. In his case, I_{ij} is defined as $I_{ij}(r) = d_M(p_i, p_j)$, see (7). Attractive forces move nodes that possess large edge weights closer to each other.

To maintain the nodes inside the prescribed location Ω, forces that pull the nodes back to the interior if they are outside the prescribed region Ω are also defined,

$$J_i = \begin{cases} 0, & p_i \in \Omega \\ dist(p_i, \Omega), & p_i \notin \Omega \end{cases}, \tag{10}$$

where $dist(\cdot,\cdot)$ is a function measuring the distance between objects.

4. Results and conclusions

4.1. Results

The presented simulation model and implemented methods were used to optimize total product distances across the factory floor. The main results of layout optimization are shown in Table 2. The layouts were tested on real historic data representing one month of production operations. The first proposed layout was designed by company experts and the last two were obtained by the force-directed graph drawing algorithm. Initially, other QAP heuristics were also tested but the presented method produced better results in terms of criterion function.

Layout	Time [days]	Total distance [km]	Relative distance
Current	30.9	690	100 %
Proposed #1	30.6	617	89 %
Proposed #2	30.2	564	82 %
Proposed #3	30.2	492	72 %

Table 2: *Optimization progress for factory floor layouts.*

On the other hand, it turns out that rearranging the machines in a practical manner does not affect total manufacturing time for completing the orders. The result is expected given that machine operation times are much longer than transport times.

4.2. Conclusions

This paper has presented a project to optimize manufacturing processes in a Slovenian furniture factory. The existing manufacturing system was analyzed by constructing a discrete event simulation model for the manufacturing processes. To speed up the analysis and optimization processes, a method for automating model construction based on input data was developed. The method analyzes open orders and constructs a corresponding model, which includes only the machines and subprocesses required for manufacturing ordered products.

The next step in the project, which is currently still active, is to optimize the machine layout. Most of the focus is placed on minimizing total transport distances the products traverse during production processes. Several QAP heuristic methods are under consideration and a force-directed graph drawing based algorithm is being developed which returns a layout with a local minimum. Preliminary results obtained from the method have indicated that it outperformed other QAP heuristics and that the overall product travel distance can be reduced by approximately 25% if the machines in the factory floor are rearranged accordingly. In the future, the method should be further tested using various data in a broader sense to ascertain whether it can compete with established methods in more general cases. Note that optimization methods provide only a basic outline of the machine layout, as company experts need to further examine and modify each case, so that the layout meets other less precise conditions.

Rearranging machine positions does not have a significant effect on total manufacturing times. Speeding up total manufacturing times would require additional machines on the factory floor to remove existing bottlenecks. This option, requiring additional expenditure for the company, will be the subject of further investigation in the project.

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