Optimisation of factory floor layout in a complex manufacturing process

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*Abstract:*This contribution describes the methods used in a factory floor optimization process. The manufacturing process involves approximately 140 machines and is concentrated around a group of multi-purpose CNC machines. We have analysed the current state of the manufacturing system by constructing a discrete event simulation (DES) model. The factory manufactures approximately 30,000 different products and half-finished products using a corresponding number of different technical processes. Due to this complexity it is not feasible to manually construct a simulation model that would include every process, and a method for automated model construction was developed. The resulting DES model reads the data on open work orders, technical procedures and bills of materials from the company database. The model is used to develop optimisation methods and verify modifications needed for process optimisation. Final part of the contribution presents the optimisation problem handled in the project: minimisation of the total distance the products need to travel between the machines. By introducing some simplifications, the problem can be described as a quadratic assignment problem. We present a heuristic method that is based on force-directed graph drawing algorithms.

Key-Words: Optimisation of processes, heuristic optimisation, discrete event simulation, factory layout, automated model construction, force-directed graphs

1 Introduction

Understanding and analysing complex manufacturing systems can be a tedious and time-consuming work since the manufacturing processes are interleaved and impossible to treat separately. Processes are usually too complex to be modelled with exact mathematical. Methods more suited for modelling of complex manufacturing systems include discrete event simulation (DES) modelling, which despite its simplicity can provide enough details to understand and analyse all processes on a factory floor.

Construction of a DES simulation model requires that the data that describe the manufacturing processes are obtained, analysed, extracted and prepared in a suitable format for the model. In order to maintain model accuracy despite changes in manufacturing processes, integration of simulation software, auxiliary applications and databases is necessary.

System optimisation or process optimisation can be performed by implementing changes in the model, usually by constructing several versions of the model and input data (i.e. scenarios) and comparing simulation results. To accelerate the development of model versions and scenarios one can construct algorithms that build or modify simulation models according to model input data. This is especially useful in cases of large simulation models and if the model variants are prepared by an algorithm, e.g. an optimisation algorithm. Automated model building and modification however requires that the model structure can be modified with an algorithm, without manual interventions.

In the paper we present main steps of the project of optimising manufacturing processes in a furniture company. Our goal was to investigate how the layout of machines on the factory floor affects the efficiency of manufacturing processes. Our primary optimisation criterion was the total distance the manufactured products need to travel on the floor, however we have also monitored various other criteria during the optimisation processes. The results of our project are used within a currently running micrologistics optimisation process.

In the paper we highlight all important steps in simulation model development and optimisation, such as preparation of databases and interaction between the programs and algorithms for optimisation.

1.1 Problem situation

Approximately 140 machines are located on the factory floor of the company. The company catalogue contains more than 30,000 different products, several of which are semi-finished products used exclusively in the manufacture of finished products within the company. Each product is manufactured according to the prescribed bill of materials (BOM) and its technical procedure. In BOM, required semi-finished products and materials to manufacture the given product are listed. The technical procedure data describe the sequence of operations in the manufacturing of the given product. The number of operations per finished product ranges from 3 to 20 with the average of 8. The technical procedure data include lists of suitable machines or groups of machines for each operation and standard machine setup and machine operation duration times. Complex products are manufactured by joining smaller semi-finished products according to the BOM. Production scheduling is based on customer orders and performed using the Preactor scheduling system. Typically, there is more than one active customer order in production at the same time. Products are manufactured in groups (series) ranging from approximately ten to several hundred pieces with a typical series containing approximately 30 pieces. After an operation at a machine is finished, the entire series of products is moved by carts and pallets to the next location (machine).

The Preactor database defines groups of equivalent machines (GEM) that can be used to perform operations defined by technical procedures. Most operations can be performed on several machines. These machines are grouped accordingly (i.e., a group of equivalent machines), with a preferred (optimal) machine defined for each group per technical procedure. Preference depends on suitability of machine for a technical procedure from the aspect of machine operation cost or operation duration. During manufacturing processes, a machine is selected from the group to perform a specific operation according to preference and machine availability. Typically a machine that is currently the least loaded in the group is chosen. Hence the manufacturing process can be referred to as “flexible manufacturing”. The simulation model has to reflect this flexibility and model the machine groups, group selection and machine selection process for each technical procedure (i.e. each product).

Manufacturing processes include large set of different products and variations of open orders during each working month. Therefore, developing a static simulation model that would cover all possible products and client's orders is not convenient. Instead, the model is built automatically from a model template, the database of technical procedures and the database of currently open orders. Technical procedures and BOMs are read dynamically from input data during the simulation. The description of data structures and model building algorithm is given in later chapters.

1.2 Previous research (review of literature)

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

Several papers deal with factory layout optimisation, with paper [8] stating that multiproduct enterprises requires a new generation of factory layouts that are flexible, modular, and easy to reconfigure. Evolutionary optimisation methods are often proposed due to problem complexity [9]. Layout optimisation problem is identified as hard Combinatorial Optimization Problem and the Simulated Annealing (SA) meta-heuristic resolution approach is proposed to solve to problem [10]. A novel particle swarm optimization method is proposed by [11] for intelligent design of an unconstrained layout in flexible manufacturing systems.

Factory layout design optimisation is further discussed in [12], [13],[14][14]. Authors [12] propose a new facility layout design model to optimise material handling costs. Sources [13] and [14]propose genetic algorithm based solutions to respond to the changes in product design, mix and volume in a continuously evolving work environment.

1.3 The manufacturing process

The furniture company has been manufacturing furniture for more than half a century. During that time, customer demands changed, the number of products, size of orders and quality requirements constantly grew. Typically, new machines were added to the workshop as needed and placed within available floor space. Machine placements were determined by experiences of foremen in the shop. Typically, the machines stayed on the same location through the years and were never moved to a perhaps better location. Some machines were replaced with newer, faster and more efficient machines, but remained at the same location. Furthermore, clients' orders and technical procedures in the company have changed over the years, thus making the current factory floor suboptimal. No systematic analysis and optimisation of factory floor layout has been made by the company.

Our task in the project was to develop a better machine layout, which will fit the current production needs and projections for the next ten years. To complete this task we have developed a simulation model of the factory floor and optimisation methods based on the company data and their specific optimisation goals. Primary goal of the company is to reduce overall costs in manufacturing processes. This can be achieved by removing bottlenecks (overloaded machines), reducing transport distances (distances the carts need to travel between the machines), reducing overall time to finish a work order or by increasing overall machine utilisations. Repositioning of the machines will be done during the upcoming renovation of the factory floor. For most of the machines there are no specific location restrictions. It is also be possible to add some new machines on the floor if considerable improvements can be achieved.

2 Methodology

Our primary objective was to develop a simulation model that captures all of the important features of manufacturing processes. The purpose of the model is verification of new manually or algorithmically generated floor layouts. Optimisation of floor layout is conducted in cooperation with experienced manufacturing planners, managers and other experts within the company, and is facilitated by state-of-the-art optimisation algorithms that are employed to generate new layout scenarios, i.e. to search for the optimal layout within a large set of possible layouts.

2.1 Existing tools and data

As a part of established scheduling and planning procedure, the furniture company uses Preactor software (http://www.preactor.com/) to schedule customer orders according to a set of priorities and availability of resources (machines) and daily monitor manufacturing processes on the factory floor. Preactor is a family of “advanced scheduling and planning” products that allows detailed definition of manufacturing and other processes and integrates with existing ERP and other company databases and applications. It allows costing, inventory control, transaction control, detailed management and monitoring of resources and orders. Since unplanned events can occur during manufacturing processes, Preactor can adapt current schedules and generate minor scheduling modifications/optimisation options.

However, the modelling process within Preactor is not flexible enough to allow easy modification of the system model or modelled processes and testing of scenarios, required for layout or process optimisation. To simulate processes in a different factory floor layout, an entire simulation model needs to be built from scratch or undergo lengthy manual modification. Preactor also does not offer physical layout modelling and 2D modelling of machine position and travel of products – this aspect is modelled as time required for transition of product between machines.

2.2 Selection of tools and methods

We decided to implement current production processes and optimisation procedure with a specialised simulation and modelling tool Anylogic – a powerful software that implement DES, SD and agent based modelling (ABM) methodologies. Modelling is performed using VIM approach which is intuitive and clear, and it supports advanced visualisations techniques. Anylogic or other simulation and modelling tools are not a replacement for advanced scheduling and planning tools as Preactor or vice versa. Instead, they complement each other: Preactor contains a detailed process model that allows accurate scheduling and planning and provides detailed process data for Anylogic, while Anylogic allows fast design and optimisation of processes, addition of new machines and verification of scenarios using different factory layouts and sets of orders. The resulting optimal or sub-optimal layout selected by the company can then be implemented in real life. Hence, Anylogic output can be used to simplify the design of a new Preactor model.

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The existing implementation of Preactor in company has significantly accelerated our modelling process in Anylogic, as nearly all the required data on manufacturing processes has already been collected and stored in a relational database. Actual factory layout described in Autocad DXF file was used to design the 2D network of machines and paths between machines in Anylogic. To illustrate, the cataloguing of all the manufacturing processes and design of database in Furniture company within the Preactor project has taken about a year to complete.

The simulation model allows us to monitor various manufacturing process statistics and to better understand the manufacturing system by discovering rules and connections in the manufacturing system. The model was verified by comparing the simulation results (e.g. manufacturing time, machine utilisation) using synthetic and real historic order data prepared by the company planners with the statistics that were generated in the manufacturing of the set of orders in the past year. The model was prepared using VIM tool (Anylogic) and can be easily adapted in order to test the effects of alterations to the manufacturing process, floor layout or the set of orders, which accelerates the optimisation process considerably.

An important part of the project was the preparation and export of manufacturing process data and customer order data from the company database and the connection of all software components (databases, simulation model, model construction application and auxiliary applications) in order to achieve the required level of integration.

2.3 Data based modelling

Manufacturing process data includes the data for technical procedures and BOM, and is stored in Microsoft SQL Server database, which serves several applications used by the company but mainly used by the manufacturing scheduling application Preactor. Preactor is used in the company for the generation and scheduling of manufacturing orders based on customer orders and for online monitoring of the manufacturing processes via approximately 100 control points. This allows the company to daily update and if necessary modify the manufacturing schedule.

We have analysed the structure and content of database tables and prepared a set of queries that were used to extract the data required for model construction and simulation scenario generation, i.e. the preparation of model input data. The queries were stored in the Microsoft SQL Server database in the form of views and later called by an Excel workbook that was used as an intermediate data storage that allowed us to examine and modify the data as required. Some corrections were necessary as the original database contained some errors and some data was missing for certain technical procedures and BOMs. This is an inevitable step when dealing with real-life data. Table 1 shows an example of an SQL query used to obtain the data on machines in machine groups (referred to as Resources and ResourceGroups).

Table 1: Example of an SQL query

```
/*Furniture company_baza_20140403.LSI.*/
CREATE VIEW Test19Projects_equivMachines AS
        SELECT ResourceGroupId, RGR.ResourceId, ResourceCode
        FROM
                Furniture
                company_baza_20140403.LSI.ResourceGroupResource
                s RGR, Furniture
                company_baza_20140403.LSI.Resources R
        WHERE RGR.ResourceId=R.ResourceId
;
```

2.3.1. Input and output data

All the input data (orders, technical procedures, BOMs, list of GEMs) are primarily stored in SQL databases, generated by Preactor software. Relevant data are saved as queries and exported to intermediate Excel file. In Excel, the data are slightly manually modified, since inaccurate and inconsistent in real data occasionally occur. In Excel, the following input data are stored:

- An order is described as a list of products (catalogue numbers). For every product from the list, name, quantity, earliest start time, priority parameter and volume are assigned.
- Each product has a specific technical procedure. For every operation there is a group of equivalent machines, a preferred machine, set up time and time per item.
- More complex products also have bill of materials, a list of required semi-finished products or materials that are joined at a specific operation in specific quantity.

At start-up of the simulation, input data from Excel are read and stored in internal arrays in Anylogic model. From there on, all data are read from internal data structures to remove constant communication with external files, which would slow down the simulation.

During simulation, various statistical data are measured and stored:

- For every pair of machines, different types of flows (number of products, number of used carts, total volume of products and total distance of carts) are measured.

- For every machine, utilisation, overall setup time, flow of products and volume, and queue of products are monitored.
- For each series of products, completion times and sequences of machines, which were chosen during simulation, are stored.
- Different, less significant measurements, such as flow of carts and routes of the carts, are recorded.

Once the simulation is finished, all the data are stored in the output Excel file,

2.4 Simulation model

The simulation model was prepared using DES methodology in Anylogic simulation and modellingtool. Anylogic stores the models as standard XML files, which allows easy manual or algorithmic modifications of the model. To this end we have developed an application in Java that reads input data from Excel and constructs the corresponding DES model by modifying a template model. Layout of machines and the underlying network of nodes describing the paths between the machines were designed according to the actual factory layout described in an AutoCAD DXF file.

Output data of the simulations, such as time, utilisation of machines, product quantity flows, supply levels and product travel distance, are stored by the model in an Excel file. This allows additional manipulation of the data and data visualisations. The schematic of a single machine in the DES model is shown in Figure 1.

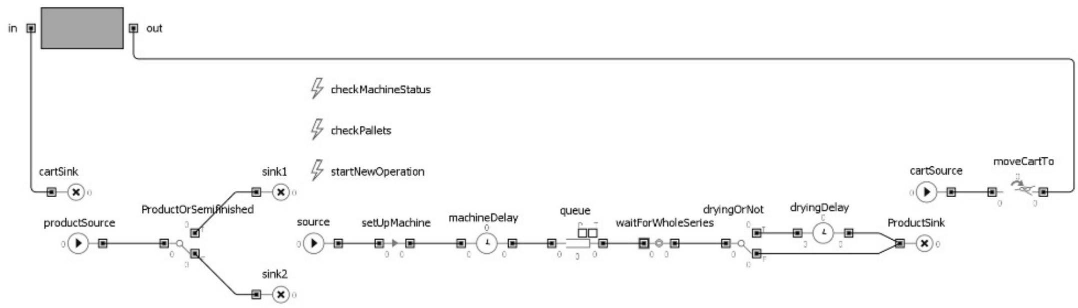

Figure 1: Schematic of a single machine in the DES model

2.5 Components of the simulation system

Modelling and simulation system is composed of four main elements:

- Core manufacturing process simulation model in Anylogic environment.
- Java application that constructs XML Anylogic model from a template file.
- MS Excel as an intermediate input and output data storage, and analysis tool.
- MS SQL server database describing technical procedures and client's orders.

The resulting system is shown in Figure 2. The simulation run is prepared as follows. First, we prepare Anylogic template file (XML). Simulation model (new Anylogic XML file) is constructed by running the Java algorithm for automatic model building. Next, we run the Anylogic simulation model. During simulation, input database is read dynamically. When simulation is finished, simulation results are stored in output Excel file.

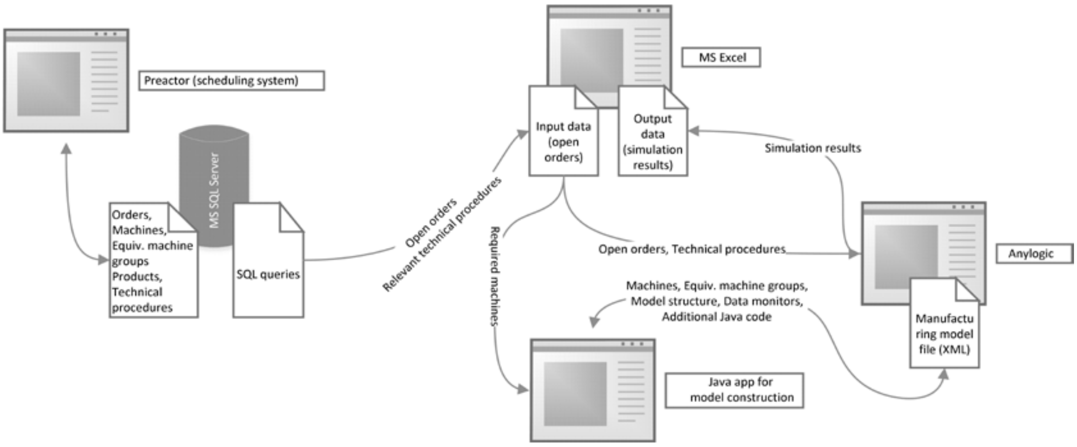

Figure 2: System schematics

2.6 Optimisation methods

In this section we describe the problem of finding the factory floor that minimises total transportation distances of the products during the production. We have tested different optimisation algorithms to minimise the total distance of the products. We have tested freely available open source heuristic algorithms in C++ and Matlab for quadratic assignment problem that are based on simulated annealing[15], iterative local approach [16][16] and ant colony algorithm[17]. We have also designed a promising heuristic optimisation method using the system dynamics (SD) methodology in Anylogic that is based on force-directed drawing algorithms and which has so far generated good results and will be further developed.

The problem is presented as finding the optimal mathematical network, in which nodes of the network represent the machines on the factory floor and weighted edges between the nodes represent transactions between the machines. Real routes on the floor between the machines are neglected in this case, since it considerably complicates the optimisation problem. The optimisation method should only propose a basic outline of the layout, since the final layout needs to be further tuned by the company experts to meet other less precise criteria.

Factory floor is described as a region Ωin the plane $\mathbb{R}^2$. We will simplify the problem by restricting Ω to the rectangular shape,

$$\Omega = \{(x,y) \in \mathbb{R}^2; x_{min} \le x \le x_{max}, y_{min} \le y \le y_{max}\} \quad (1),$$

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

Let us denote machines by $m_i,\ i = 1,2,\dots,N$. Position of the machine m_i is described by

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

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

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

For every pair of machines$m_i$and $m_j,\ i,j = 1,2,\dots,N$, we obtain a flow of products $f_{ij} \ge 0$ as a result of the simulation of the manufacturing processes.

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

The optimisation problem of minimising the total distance is described as

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

where positions p_i must satisfy the conditions

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

for every $i \ne j$ and

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

for every $i = 1,2,\dots,N$.

The first conditions states that the regions of machines must not intersect between each other and the second that every machines must lie entirely in the factory flow.

For every layout of machines one would also need to define a suitable network of routes. To simplify the tedious problem of defining the network from the machine positions, we presume the distance between the machines is a well-known Manhattan distance,

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

Since the original routes in the factory are defined on a rectangular grids, differences in lengths of paths, if we use the functional $d_M$instead of$d$, are small.

If we presume that all machines take the same amount of space on the floor (all r_i are the same) we can restrict the positions p_i to discrete points on a predefined grid. Hence the problems simplifies to well-known quadratic assignment problem.

2.7 Force-directed graph drawing algorithm

In this section we will present a heuristic optimisation algorithm for assigning positions p_i to machinesm_i. The algorithm is based on force-directed graph drawing methods. Every machine is presented as a node on a plane. To every node n_i we prescribe the corresponding repelling force F_{ij} to all other nodes n_j,

$$F_{ij} = H_{ij}(||p_j - p_i||_2) \cdot \frac{p_j - p_i}{||p_j - p_i||_2}, \qquad (8)$$

whereH_{ij} is a positive monotonically decreasing function. Typically, H_{ij} is defined as $H_{ij}(r) = r^{-2}$. Repulsive forces keep the nodes away from each other since we want sufficient space between the machines.

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

$$G_{ij} = -f_{ij} \cdot I_{ij}(||p_j - p_i||_2) \cdot \frac{p_j - p_i}{||p_j - p_i||_2}, (9)$$

whereI_{ij} is a positive monotonically increasing function. In our case, I_{ij} is defined as $I_{ij}(r) = d_M(p_i, p_j)$. Attractive forces move the nodes with large edge weights closer to each other.

To keep the nodes inside the prescribed locationΩ, we also need to define forces that pull the nodes back to the interior if they are outside the prescribed region Ω,

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

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

3 Results and discussion

In this phase of the project the deliverables include an integrated simulation model in Anylogic that communicates with external database files and the method for automatic model construction. The model servers as an indispensable tool for in-depth analysis of the manufacturing process.

An important result is also a developed heuristic method that proposes a new layout machines on the factory floor to minimise the total distance of the products. The method outperformed other more general heuristic methods for QAP in terms of the optimisation criterion. The newly proposed layout has around 25% - 30% shorter total product travel distance than the current layout. Shorter travel also means less time is required for transport of products. As transport is performed by workers pushing the carts, this means that fewer carts and workers will be required. Other workers can then be relocated on other assignments on the factory floor. The customer has responded very favourably to these results, and is willing to implement the suggested changes. They have also prepared several manually adjusted floor layout based on our generated layout and submitted them to us for verification with the simulation model.

An interesting discovery is that the optimisation of layout for shortest product travel distance only negligibly affected the total manufacturing time for the given set of orders. The result is however predictable since machine operation times are much longer than transport times. Further steps in our project will include alterations to the set of machines: replacement of one or several machines by newer multipurpose CNC machines. Other optimisation goals and criteria will be explored.

To significantly reduce the total manufacturing time, the company would need to buy additional CNC machines to remove the existing bottlenecks - several CNCs have a very high (70%+) utilization. As CNC machines are expensive, purchase of new machines will be considered only in the frame of within a currently running micrologistics optimisation process, which includes new transport methods such as conveyor belts and automated carts.

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