Process performance analysis and layout optimization for a medium-sized manufacturing enterprise

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Abstract

For estimating the potential for process improvement for a medium-sized mechanical manufacturing enterprise, a study was performed. The goal was to identify potential for throughput time reduction and for improvement of the material handling by layout optimization of the factory. The study is based on statistical data analysis of historical order processing data.From these data, the flow of the orders through the production system as well as dynamical properties of the order flow like, e.g., waiting times at the working stations, was derived.

The results show that there is a large potential for reduction of throughput time. The ratio of waiting times to processing times is quite large compared with reference values from analytical queuing systems and benchmarks.

Based on the quantitive data of the order flow, both a manual and a numerical layout optimization was performed. With both methods, a significant reduction of the total transport way compared with the actual situation could be achieved. However, the numerical approach was significantly better than the manual approach.

1. INTRODUCTION

Büchi AG in Wil SG, Switzerland, is a mechanical manufacturing enterprise that produces sheet metal devices in a small or medium series production. Its customers typically are regionally located companies, for example in the machine building industry. Büchi AG has about 30 employees and processes about 6000 orders per year.

In order to improve both the internal manufacturing process management and the physical layout of the production site, a study with the Institute for Data Analysis and Process Design (idp) of the Zurich University of Applied Sciences was performed. The goal of this study was an analysis of the production flow, both in terms of material handling (transport) and in terms of operations (throughput time) for identifying and quantifying optimization potential.

The layout of the production site has been evolved historically over a long period of time and was expected to be sub-optimal. Thus, an analysis of the potential of layout optimization was made. From the operational point of view, a reduction of throughput times would be highly advantageous due to increasing market demand on shorter response times. Therefore, the potential for a reduction of throughput times was investigated.

The study is based on a data analysis of historical production data. This data is used in two kinds: First, the requirements for the production system can be evaluated. For example, the path of the orders throuhg the production system is different for each order. A quantitative analysis of the orders clarifies the transport requirements between the different working stations. Second, the data is used for analyzing the present status of order processing, in particular regarding waiting times. Comparing these values with reference values shows optimization potential.

2. STRUCTURE OF THE PRODUCTION SYSTEM AND DATA

Büchi AG has a classical job shop structure consisting of 20 operation centers (called stations in the following) performing a specialized task and typically being equipped with a special machine. Examples of such stations are laser cutting, punching, bending, and welding. Each order consists of different production steps at the different stations. At each station, typically the work is processed in one batch. The different orders vary not only in the number of items to be produced but also in the kind and number of working stations.

Once an order is received, its processing is planned in the production planning department. Some days before due time of the order, it is dispatched into the production system. Within the production, the jobs are processed mainly on a First-Come-First-Served scheduling rule, with the exception of urgent orders.

For the presented study, the analysis was based on production data from the last two years. The orders are managed in a production information system where the processing and completion of each working step is monitored in the following way: Each order is identified by a unique bar code pattern. Additionally, each working station has a special bar code labeling. Each time a worker begins to process a certain order, he moves a bar code reader over the bar code of the order and the bar code of the actual station. This leads to a new record in the production information system (cmp. **Figure 1**). Similarly, the end of the work on this order is captured by the bar code reader. Such, for each work step, the start as well as the working time are recorded.
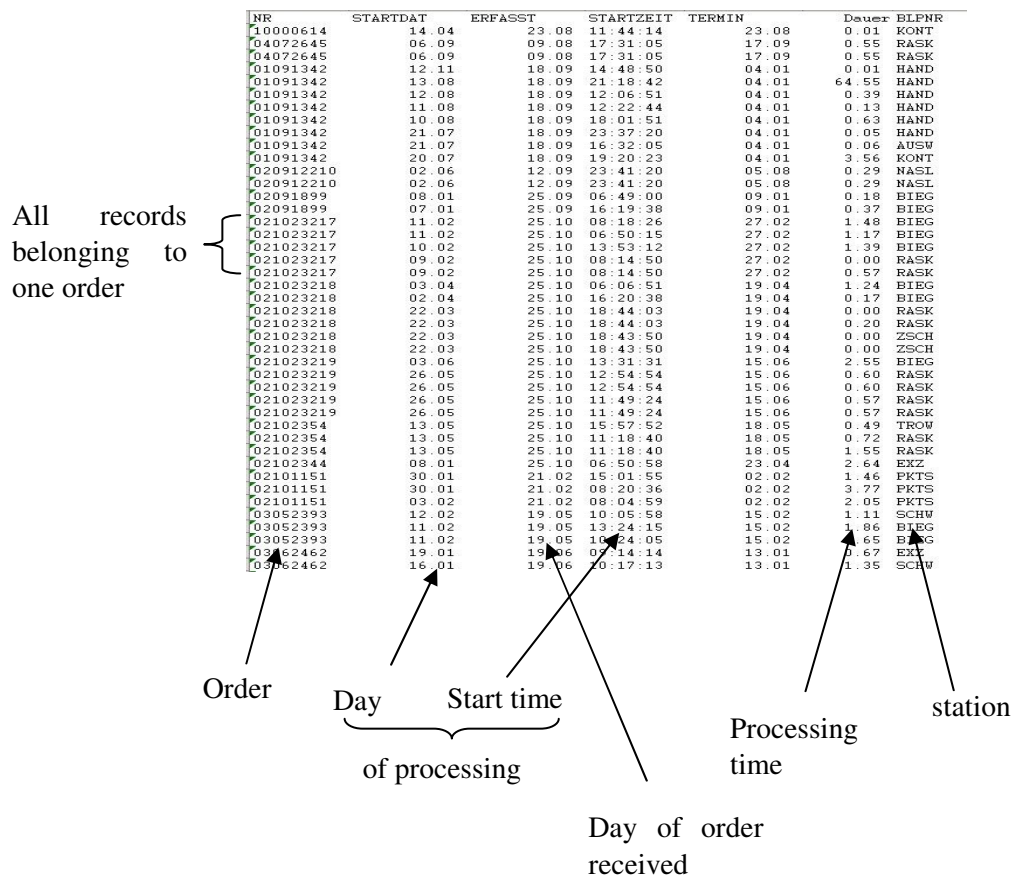
Figure 1: Example of raw data of the production information system. Each record denotes one processing action in the order completion process. Since the processing at one station may be interrupted due to breaks, a station may have several records in this list.

If the work is interrupted due to a break or because the end of the day is reached, the worker signals end of work. When he restarts his work, a new record is created. Thus, for each order, all processing periods at the different station are recorded (**Figure 1**).

From this information, the flow of the order through the different stations can be reconstructed. Waiting times between succeeding stations can be reconstructed. Also, the effective processing times for a station can be calculated.

3.   ORDER PROPERTIES AND ORDER PROCESSING

3.1   STATISTICAL PROPERTIES OF THE ORDERS

In order to optimize its operational performance, a company should match its internal processes as much as possible to the dynamical demand of the market which, in the considered case, consists in arrivals of different orders. In the design phase, the statistical properties of the orders are of primary interest. Also, for estimating the potential for improvement, these properties are central.

From the data, the following important features of the market demand could be derived:
- On the average, an order consists of 2.3 stations. However, there exist many orders with only one station; on the other hand there are orders with more than six stations.
- On the average, about 20 orders per day are processed.
- The mean total processing time of an order is 4.8 hours.

3.2   FLOW OF JOBS THROUGH STATIONS

From the available data, the flow of the orders through the different stations can be derived quantitatively. For describing the flow, the transitions between the different stations for all orders during the analyzed time period were counted. In **Figure 2**, the flow of orders through the production system is displayed graphically. The numbers on the arrows indicate the number of orders that, during one year, flew along this path. Large numbers denote frequent transitions. For the improvement of readability, transitions with few orders have been suppressed.

It can be seen that the different transitions differ heavily in their strength. Some transitions have several hundred orders, while other transitions have only few orders. Furthermore, there are stations that are typical initial stations, e.g. NASL and RASK that both are laser cutting machines. Other stations are typical end stations like SCHW (welding station).

This quantitative information is central for optimizing the physical material flow. Since the transport units for the material is standardized pallets, the derived numbers indicate the transport requirement for the different transitions.

3.3   PROCESSING TIMES AND THEIR DISTRIBUTION

The processing times at the different stations have been analyzed statistically. The mean processing time at the different stations varies between 1 and 5 hours. For most of the stations, the mean processing time is between 2 and 3 hours. Averaged over all stations and orders, the mean processing time is 2.1 hours.
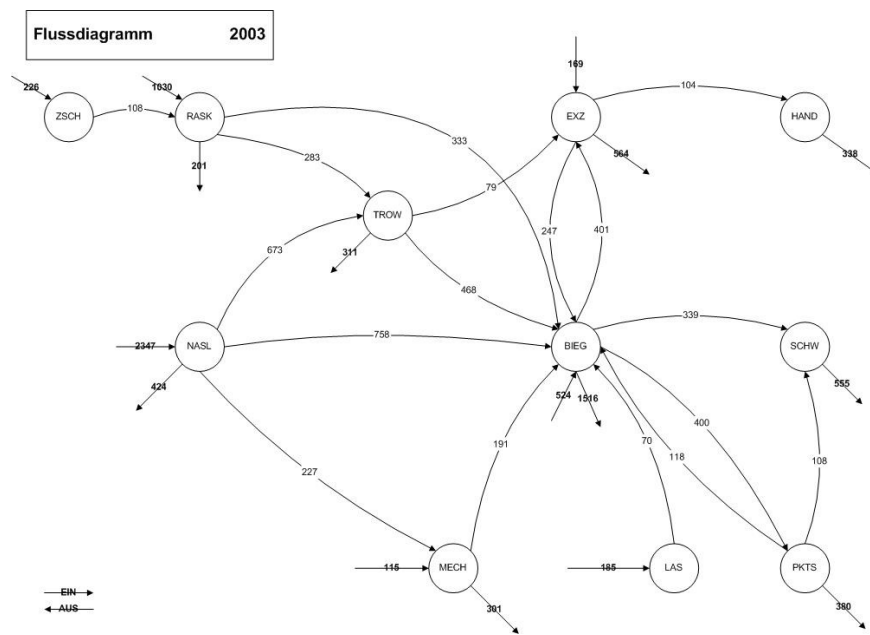
Figure 2: Graphical display of order flow through the different stations. The numbers at the arrows indicate the number of orders that flew along this path. Transitions with few orders are suppressed for the sake of readability.
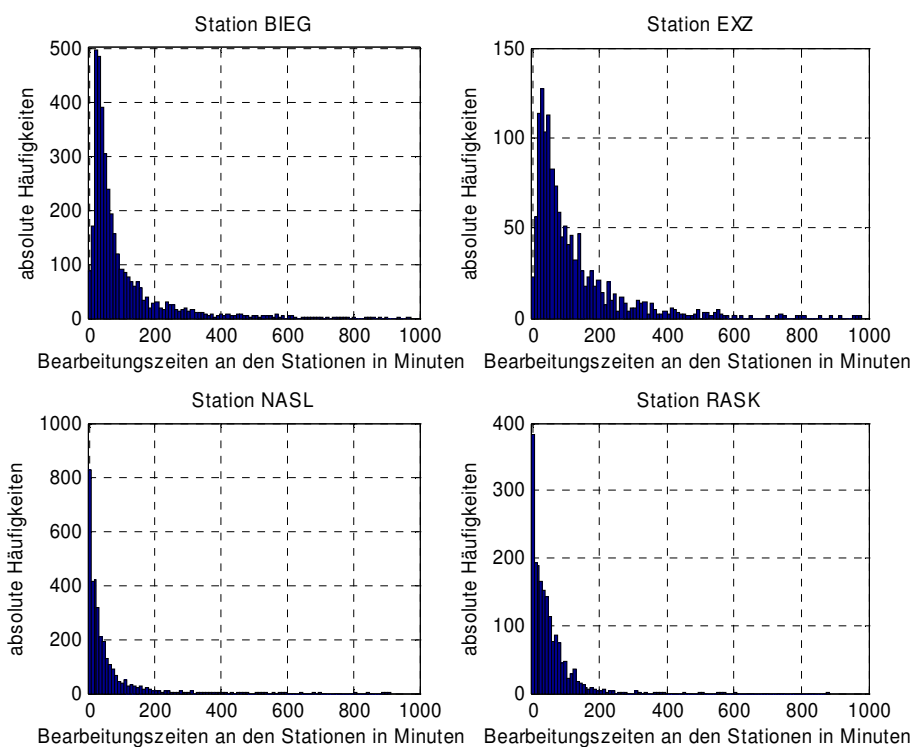
Figure 3 : Histograms of the processing times for four typical stations. The found distributions are in all cases close to exponentially distributed, except for processing times that are very short (e.g. for station BIEG). Here a deviation from exponential distribution can be seen at some stations.

The processing times show large variability. However, for all stations, the processing times are nearly exponentially distributed (see **Figure 3**). Deviations from the exponential distribution can be seen for very low times. This is clear since an order cannot have an arbitrary small processing time.

From the practical point of view, the existence of an exponential distribution indicates large variability within the work load of the different orders. This implies delays in the order flow and leads to an increase of throughput time. In [2], the effect of variability on operations is discussed. From a statistical perspective, the exponential distribution is a standard model for describing the variability of the processing times. Most classical analytical solutions from queuing theory are based on exponentially distributed processing times and can thus be applied [1].
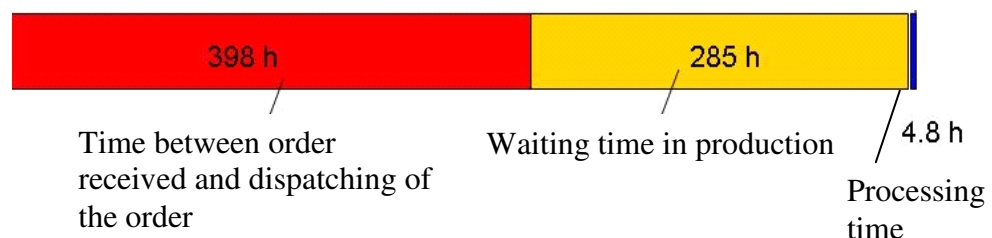
3.4   THROUGHPUT TIMES

The throughput times for the orders are recorded and can be evaluated statistically. In a first step, it was distinguished between
1. the time between order received and dispatching of the order to the production department
2. the waiting time between the stations in production
3. the processing time at the stations

In **Figure 4**, the distribution of the total throughput time over these three categories is shown. It can be seen that the orders spend most of the time not in the production system but in the production planning department. This is due to the production planning philosophy which tries to keep the number of orders in the production system at a minimum. Thus, orders are transferred into the production department as late as possible.

The time within the production system consists of 285 h of waiting time and 4.8 hours processing time. Consequently, an improvement of throughput time can only be achieved by an improved management of waiting times. In order to further investigate the waiting time, the relation between throughput time and number of stations of the order was investigated. In **Figure 5**, the mean throughput time in the production in dependence of the number of stations of the order is displayed, measured as the time between the start of the first processing step and end of the last processing step. If the order is to be processed at only one station, this time corresponds to the processing time plus times for breaks. If the order consists of more than one station, the measured time includes the waiting time between the stations.

Figure 4 : Segmentation of throughput times in (a) time between order received and dispatching of the order, (b) waiting time in production, and (c) processing time.
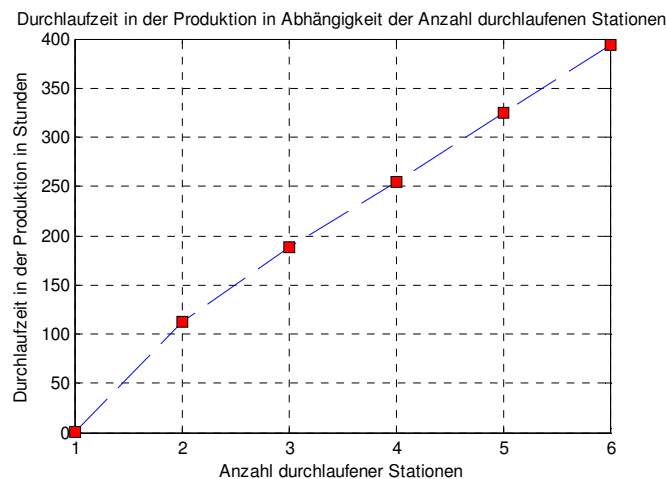
Figure 5 : Throughput time in production department in dependence of number of stations.

As can be seen in **Figure 5**, an additional station increases the throughput time by about 70 hours which corresponds to about three days. Note that the pure processing time of an additional station is, on the average, only around 2 hours for most of the stations.

For the whole company, one can state that the total throughput time is, on the average, about 140 times larger than the processing time. If only the production system is regarded, the throughput time is about 63 times larger than the processing time.

Since the statistical analysis has shown that the processing times are distributed nearly exponentially, and since the order income from the side of the customers can be assumed as a Poisson process, the analytical framework of Jackson networks can be used for deriving a rough reference value for the throughput times (see [1] for details). Jackson networks are a common model for job shop architectures. They assume a random arrival of orders as Poisson process, exponentially distributed processing times at the different stations, and a FIFO priority rule for scheduling. Jackson networks ignore any improvements by production planning and assume that orders are fed into the production immediately at arrival.

For Jackson networks with uninterrupted processing (24 hours at 7 days per week), and a utilization of the stations of 90%, one gets a factor 10:1 for total throughput time:processing time. When a two-shift operation (16 hours daily working time) at 5 days per week is assumed, this factor increases to about 20:1. Empirical values for industrial production sites result in benchmark values of 5…10% of processing time, compared with the total throughput time. This is roughly compatible with the Jackson network calculation.

Compared with these references, the measured throughput times are rather high indicating considerable potential for reduction of throughput times.

4. LAYOUT OPTIMIZATION

The physical layout of a production site is important for the operational efficiency. Among others, important factors are minimum transport distances, clearly designed transport ways, and appropriate space for storing the work in process. For the present investigation, the focus was on the minimization of the transport distances.

Each order begins at the inventory of the raw materials, passes the different stations, and, finally, has to be transported to the inventory of the finished goods. The following measure for the total transport costs was used:

$$C = \sum_i \sum_{j=1}^{M_i+1} d\big(s(j-1,i), s(j,i)\big)$$

where i denotes the order, and j numbers the stations that order i has to pass. The quantity M_i indicates the number of stations order i has to pass. s(j,i) denotes the jth station (j=1,..,M_i) of order i, where s(0,i) is the inventory of the raw materials (starting point for each order), and s(M_i+1,i) is the finished good inventory. The distances between two stations s and s' is measured by d(s,s') and is expressed in meters.

Thus, C measures the total transport distance over all considered orders. For this study, all orders of a complete year were considered. The present layout of the production site leads to a total transport way of 638 km which is used as a reference value for the optimization.

The potential analysis focused on an optimized spatial arrangement of the working stations leading to reduced transport ways. As a simplification, the different space requirements for the different stations were ignored, replacing the stations by equally large "normalized" stations. The mean distance between the stations has been set to 12 m which corresponds to the present situation in the factory. A rectangular factory area has been assumed consisting of a single floor.

4.1 MANUAL OPTIMIZATION

In a first stage, the calculated flow diagrams have been analyzed. As a rule, frequently occurring transitions should have a short transport distance, where rare transitions can have larger distances. With this rule keeping in mind, an optimized layout was developed manually. The result is shown in **Figure 6**. The stations EIN and AUS are additional stations indicating the raw material inventory (EIN) and the inventory of the finished goods (AUS).

The frequently visited stations are indicated in red. Other stations, that are rarely used, are indicated in black. Their position is not relevant for the total transport way. In a first step, the frequently visited stations have been placed, at a minimum distance of 12 m from one station to each other. In a second step, the rarely used stations were placed in order to fill the empty space of the factory floor.

The resulting factory floor has a size of 80x45 m. With this design, a total transport way of 443 km resulted. Compared to the present situation, this corresponds to a reduction of 31%.

4.2 NUMERICAL OPTIMIZATION

In a second stage, a numerical optimization algorithm for the factory layout optimization was developed. The following optimization problem was solved:

$$C = \sum_i \sum_{j=1}^{M_i+1} d\big(s(j-1,i), s(j,i)\big) \overset{!}{=} \min.$$
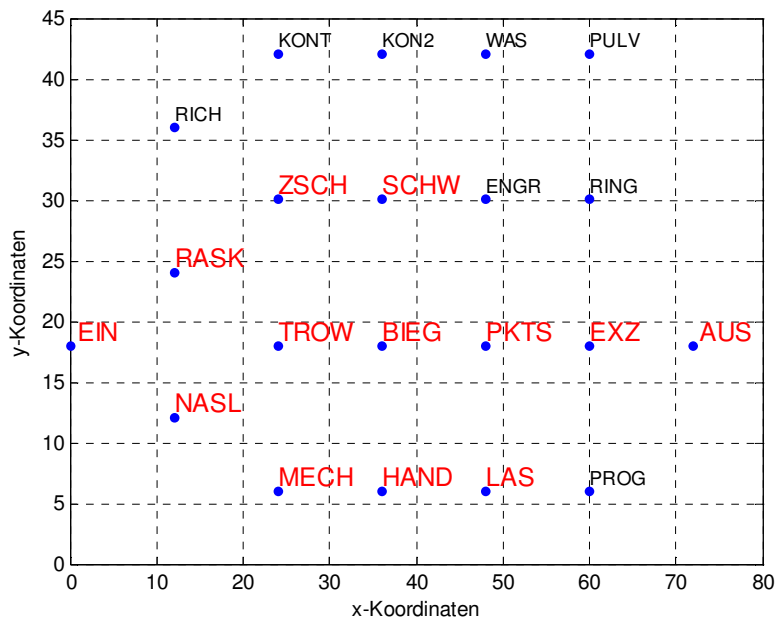
Figure 6 : Manually optimized layout. The stations EIN and AUS are additional stations indicating the raw material inventory (EIN) and the inventory of the finished goods (AUS). The coordinates are measured in meter.

with additional boundary constraints that made sure that the mutual distance between the stations was 12 m or more.

The optimization algorithm was implemented in MATLAB, using the optimization toolbox. A mixture between Nelder-Mead algorithm and a gradient based minimization was used. The result of the numerical optimization is shown in **Figure 7**. The resulting total transport way for the optimum layout is reduced to 302 km which corresponds to an additional improvement of 32% compared to
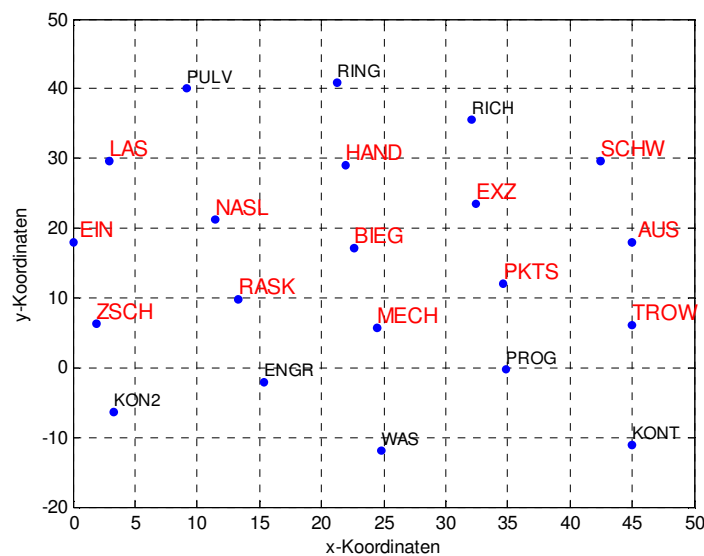
Figure 7: Numerically optimized layout.

the manually optimized layout. Compared to the original layout, a reduction of 52% can be achieved.

When comparing with **Figure 6**, it can be seen that the distance between EIN and AUS is shorter. On the other hand, the extension in y-coordinate is larger. The dimensions of the factory floor now are 50m x 70m, compared to 80m x 45m. A deeper analysis shows that it is crucial for the transport optimization that the dimensions of the floor are chosen correctly. If the dimensions of the manually optimized floor are kept fixed, it is not possible to reduce the transport way significantly by re-arranging the stations. Thus, one can conclude that factory dimensions of about 50m x 70m are necessary in order to achieve the minimum transport way.

4.3   COMMENTS

Of course, the above described layout optimization is only a first step for the final layout optimization. Especially the fact that all stations have been assumed to have the same size is not realistic. For the final design, the different sizes have to be taken into account. Additionally, for realizing a new factory building, additional restrictions have to be considered. However, this does not constitute a major problem for the numerical optimization.

The presented study shows, however, that there is a major potential for improvement which is in the order of 50%. Even if a manual optimization based on the orders flows already led to a large reduction; the use of numerical optimization methods led to a further significant improvement.

4.   CONCLUSION

A study was performed for analyzing the potential of process flow improvement of a medium-sized Swiss manufacturing company both from the physical point of view (reduction of transport distances) and from the operations management view (reduction of throughput times).

To this aim, a statistical analysis of the order flow through the production system was performed. From this analysis, the strength of the transitions between the stations could be evaluated quantitatively. Furthermore, the analysis revealed the magnitude of the waiting times both within the production planning department and the production site. A statistical analysis of processing times showed a near-to-exponential distribution which allows using standard analytical queuing models.

The two main results of the study are:
- The ratio of waiting times and processing times is rather high compared with analytical references and benchmarks. This indicates a high potential for reduction of throughput time by improved process control.
- The physical layout can be drastically improved. A reduction of about 50% seems realistic for a rectangular factory floor of about 50m x 70m.

REFERENCES

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[2] W.J. Hopp, M.L. Spearman: Factory Physics. McGraw-Hill, 2000.