BAKERY PRODUCTION SCHEDULING OPTIMIZATION – A PSO APPROACH

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ABSTRACT
Production of bakery goods is strictly time sensitive due to the yeast proofing of doughs. That causes special requirements for production planning and scheduling, which is in bakeries often completely based on the practical experience of the responsible employee instead of mathematical methods. This often leads to sub-optimal performance of companies due to the sometimes “chaotic” scheduling approach. This work presents an approach to use PSO as a highly efficient numerical method to solve complex scheduling problems. In all probability bakeries will be able to increase efficiency by optimizing their production planning with numerical methods like the one presented here. After modelling the production line with a limited range of input data and a pre-processing of the necessary data to match the real process induced requirements, a PSO algorithm handles the optimization task. Results show the high potential of this method to solve the scheduling problem in good computational time.

Keywords: production planning, baking industry, scheduling, particle swarm optimization

1. INTRODUCTION
A high number of bakery goods contain yeast (*Saccharomyces cerevisiae*) as a proofing agent. Due to the fact that this form of proofing is a fermentation performed by microorganisms in which sugars are metabolised to CO_2 (among other components), the production of such goods is not highly but strictly time sensitive from the point on where the microorganisms get in contact with water and substrates, as happens in the dough making process. Since it is costly to regulate or slow down the fermentation speed of yeast by cooling and its sometimes negative influence on the product quality on the one hand and the decrease of product quality (up to the total loss of marketability) due to a too long fermentation process on the other hand, the time dependency of the processing has always to be considered in the production scheduling.

Focusing on the German baking industry the production planning is almost completely based on the practical experience of the responsible employee(s) instead of the usage of mathematical methods like scheduling or optimization theory. Combined with the high diversity of the product range that includes around 100 different products in a common German bakery and the high complexity of the scheduling task induced therein the performance of bakeries is often sub-optimal. The use of numerical methods like particle swarm optimization (PSO) to solve the scheduling task might increase the efficiency of companies by calculating an optimal production plan and by that determine the exact time schedule and capacities of devices needed to reach the production goal. Thus idle times of machines can be reduced or completely erased which leads to a reduction of energy consumption.

The German baking industry consists of approximately 16000 companies that produce about 6.25 billion tons of baked goods with a business volume of almost 12 billion Euros per year and employs over 275000 employees. Thus the increase of companies' efficiency in respect of e. g. energy consumption or staff allocation and working hours comprises a high potential to decrease production costs in this industry.

After its invention by Kennedy and Eberhart (Kennedy and Eberhart 1995) PSO was widely used to tackle numerous scheduling or optimization problems in many different industry branches (Eberhart and Shi 2001; Lian, Gu and Jiao 2008; Liu, Wang, Liu, Qian and Jin 2010; Pan, Tasgetrien, and Liang 2008; Tasgetiren, Liang, Sevkli and Gencyilmaz 2007; Wang and Yang 2010). As a swarm intelligence algorithm it mimics the behaviour of animal swarms like fish schools or bird flocks and iteratively searches the search space for the optimal solution. Since PSO provides easy implementation, easy modification and the ability to solve high complex scheduling or optimization tasks in short computational time it is an appropriate method to solve the bakery scheduling problem.

2. MATERIAL AND METHODS

The developments and investigations presented here were performed on a “lenovo ThinkPad R500” with an “Intel Core 2 Duo” 2.26 GHz processor, 2 GB RAM and Microsoft XP 2002 as system software. The modelling and optimization were made with MATLAB 7.1 (The MathWorks, Inc) and the visualization and validation of the optimization results with ARENA 11.0 (Rockwell Automation, Inc).

3. MODELLING AND OPTIMIZATION

Due to the high diversity of products in a German bakery it is not possible to solve the scheduling task with exact methods, at least not in reasonable computational time. Using an exact method to calculate the parameters of all possible schedules would mean to calculate an enormous number of combinations given by the relation in equation (1), where *n* is the number of jobs (products) and *m* is the number of machines used.

$$number\ of\ schedules = (n!)^m \qquad (1)$$

It is obvious that this relation causes an almost unmanageable amount of combinations for the scheduling problem in German bakeries, where the normal range of products is commonly above 100 and the machinery in operation between 10 and 50 (depending on the bakery’s size).

From the scheduling point of view the production in a bakery can be described as a *hybrid flow-shop* according to the common definitions, e. g. in (Pinedo 2008; Ruiz and Vázquez-Rodríguez 2010).

The number of possible schedules can be reduced significantly by considering the scheduling task in a bakery as a *permutation flow-shop* instead of a ‘normal’ *hybrid flow-shop* by adding the constraint that the order in which the jobs *n* pass through the production is fixed and does not change between production stages (Pinedo 2008; Lian, Gu and Jiao 2008; Tasgetiren, Liang, Sevkli and Gencyilmaz 2007). Although the real process in a bakery does not fulfil this requirements entirely this model can be used and modified to match with the real production processes, where products can bypass other previously started products. By doing so the number of possible combinations is reduced from $(n!)^m$ to $n!$ and each schedule is a permutation of *n* (Perez-Gonzalez and Framinan 2010). Each of those permutations is used then to determine a sequence of products on the first production stage of the bakery that is crucial for sequencing the work flow. Still $n!$ different schedules may easily lead to optimization problems unsolvable with exact methods in reasonable computational time for high numbers of *n*.

Additionally the scheduling in a bakery is subject to a no-wait constraint due to the fact that there are very small tolerances for waiting times of yeast containing doughs/products.

3.1. Modelling of the production processes

The modelling of the production site and the compliance of the no-wait constraint are done prior to the actual optimization of the scheduling.

As first step a matrix *A* is formed that contains all processing times (*PT*) of the products to be produced. The rows and columns of the matrix represent the products and the production stages respectively, such that e. g. $a_{2,3}$ would return the processing time of product 2 on stage 3, meaning in this case that the product “Dinkelbrot” requires a dough rest of 30 minutes. The processing times are determined by the recipe and the desired characteristics of the finished product. Basically all products follow the same way through the production on consecutive stages, meaning that a product does not return to an already passed stage. The common progression of production stages in a bakery is shown in Figure 5. Some products do not require processing on a certain stage (e. g. if a product needs no dough rest) and skip it. A zero entry in the matrix *A* indicates that the product skips the respective stage and is not processed there.

The information contained in such a matrix is given as an example in Figure 1 (the production line data used for one of the examples presented here).

Product/Process	Ingredients Preparation	Kneading	Dough Rest	Dividing and Forming	Proofing	Baking
Korn Eck	10	9	25	11	30	50
Dinkelbrot	8	9	30	16	45	50
Körnerbrot	10	9	20	20	50	60
Annabrot	5	9	20	16	50	63
Holzlucken	5	9	15	21	70	55
Mischbrot 500g	5	8	15	31	60	53
Mischbrot 1kg	5	8	15	26	60	55
Bauernbrot 500g	5	9	20	31	60	55
Bauernbrot 1kg	5	9	20	26	60	60
Fitnessbrot	5	9	20	31	60	50
Kartoffelbrot	8	15	20	25	40	45
Doppelbrot	5	9	20	31	60	40

Figure 1: Processing Times of Products (Line 1)

Based on this matrix the starting times of all products on all stages are calculated for the investigated sequence of products (which represents a particle in the PSO) and form a new matrix *B*.

To make sure that no product waiting times appear during the optimization process (and the no-wait constraint is not violated) the calculation of the products’ starting times on the respective stages uses the following steps:

1. The starting time (*ST*) of product 1 (first product of the sequence) on the first stage is “0” as this represents the start of the production.

2. The starting times of product 1 on the following stages *m* are simply a summation of the processing times (*PT*) on the previous stages as given in equation (2), where *j* is job (or product) 1 and *m* is the current stage calculated.

$$ST_{j,m} = \sum_{n=1}^{m-1} PT_{j,n} \quad (2)$$

3. From this first row in matrix *B* the starting times for the next product in the sequence are calculated by first picking the adequate starting time on the last stage m_{max}. The "adequate" time means the *ST* that makes sure that no waiting-time will occur and is determined by following equation (3), where $j = 2, 3, \ldots, j_{max}$ and $m = 1, 2, \ldots, m_{max}$.

$$ST_{j,mmax} = \max(ST_{j-1,m} + PT_{j-1,m} + \sum_{n=m}^{mmax-1} PT_{j,n}) \quad (3)$$

   Since there are often stages in a bakery production that have a practically unlimited capacity (subject to the condition of sufficient dimensioning), like proofing chambers or the dough resting that is often performed by just put the dough aside for a certain time span, only stages with limited capacity are considered for choosing $ST_{j,mmax}$.
   Thus it is made sure that a possible "bottle-neck" in the production line will have the deciding impact on the calculation of the *ST*.
4. After $ST_{j,mmax}$ is determined the other starting times for product *j* on stages *m* are calculated by just subtracting the respective $PT_{j,m}$ to form the matrix *B*. Thus no waiting times for products will appear in the schedule.
5. To assure an optimal scheduling within each investigated product sequence and to allow the skipping of stages or the bypassing of other products each row in *B* (which represents a product) is compared to a set of conditions during its calculation process to create the best possible schedule setup.

The progress of the modelling algorithm is shown in the flow chart in Figure 2.

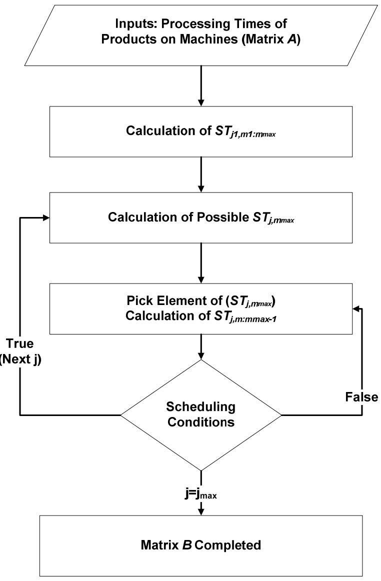

Figure 2: Flow Chart of Modelling Algorithm

3.2. Particle swarm optimization

The PSO method is capable of solving scheduling problems with high complexity and easy to implement due to the relative low input data needed. It follows the basic algorithm shown for an example in the flow chart in Figure 3.

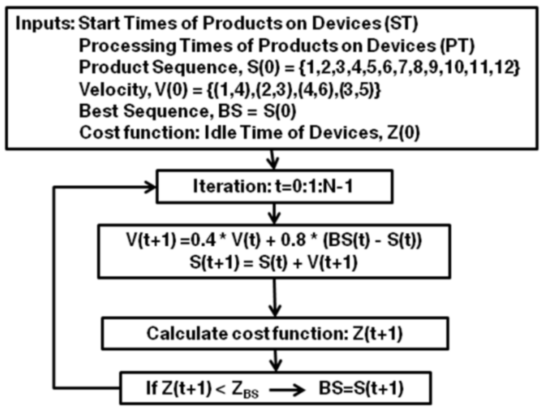

Figure 3: Basic PSO Algorithm

The cost or objective functions to be evaluated could be e. g. the idle time of machines (as presented in the example), the minimum total idle time of machines, utilization of machines, the makespan or other objectives of economical interest.

During the iterations of the algorithm the particles are "flying" through the search space and due to the frequent update and comparison of the best sequence so far and each particle's current value of the cost function, move to the optimal solution of the given optimization problem. Figure 4 shows this behaviour of the algorithm by illustrating the "flight" of a particle towards the optimal solution (in this case the minimum of a cost function).

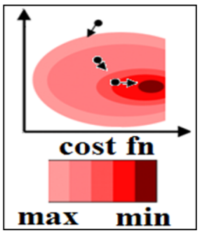

Figure 4: Particle "Flight" through the Search Space

3.3. Visualisation and validation of PSO output

The simulation software ARENA 11.0 (Rockwell Enterprises) was used as a visualisation tool for the production line investigated. A production line model was built out of predefined modules (setup shown in Figure 5) in the software and the relevant production sequences were simulated.

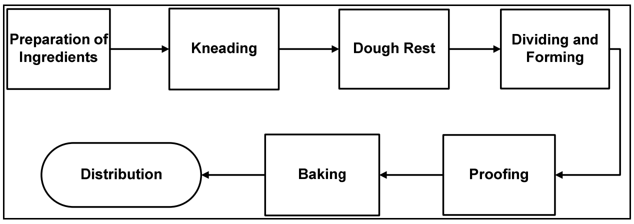

Figure 5: Production Line Model

Thus it was possible to further investigate the flow of each product through the production line and to validate the performance of the numerical generated best production sequence.

3.4. Example optimizations

Two bakery production lines were modelled and optimized as example applications. The first line, taken from a medium sized baking company that runs 53 chain stores, produces 12 different kinds of bread using six different stages/machines. The second line is taken from a small bakery workshop with just two chain stores that produces 10 different bread products on a comparable machinery setup (but with other dimensioning). The 12 products in example one and the 10 products in example two give a total of 479.001.600 (n!=12!) and 3.628.800 (n!=10!) possible different sequences respectively if the production line is handled as a *permutation flow-shop*.

Thus it would be a time consuming procedure to solve these setups by calculating each possible schedule to find the optimal one. So the aforementioned PSO method proposed here was used to find the best schedule.

The processing times of the products and the used machines of example one are given in Figure 1 and for example two in Figure 6. The general line setup for both is shown as a model in Figure 5. Since the time sensitivity of dough or bakery products ends with the baking process the investigations of the production lines end with this process step and the picking of products for distribution was not added to this analysis.

ARENA as a simulation software provides the possibility to validate the optimization output by defining the ARENA model parameters according to the optimization results. Also it is possible to plot the utilization of each process module and thus can be used to visualize e. g. utilization gaps or the different utilization of machines according to the investigated product sequence.

Product/Process	Ingredients Preparation	Kneading	Dough Rest	Dividing and Forming	Proofing	Baking
Baguette	10	5	20	15	45	30
Dinkelbrot	5	7	15	20	50	60
Mischbrot	7	10	30	30	60	55
Roggenbrot	10	8	10	25	45	60
Kosakenbrot	8	9	25	15	55	60
Weißbrot	5	15	45	30	60	35
Körnerbrot	8	10	20	30	50	45
Fladenbrot	7	6	15	35	60	30
Genetztes Brot	9	7	35	20	45	55
Bauernbrot	5	5	10	16	50	45

Figure 6: Processing Times of Products (Line 2)

3.5. Optimization results

For both example lines the minimization of the total idle time was the objective function. The idle time of a machine means the time a machine that is free and able to process a product has to wait for a product that has not yet finished its processing on a previous machine. In many cases this idle time means a waste of energy because the machine stays in a stand-by mode. In the case of bakery devices the idle time of an oven is the most important factor regarding potential energy savings because an oven has to be heated to remain in stand-by. But besides the oven stage every idle time of other devices means a waste of energy.

The capacity limited stages on both lines are stages one (preparation of ingredients), two (kneading), four (dividing and forming) and six (baking). All those stages can only handle one product batch at a time. The two other stages in the production line (dough rest and proofing) are practically unlimited for the investigated scenario due to their ability to handle several product batches at the same time.

As initial sequences on both investigated production line examples the real process sequences were taken as used in the two companies (shown in Figure 1 and 6 respectively). First the total idle times for both lines were calculated as reference values. After that the optimization procedure was used to find the sequence holding the minimal total idle time, which is the optimal sequence in the analyzed case. The results for both examples are shown in Table 1.

Table 1: Results of Optimization for both Production Line Examples

Production Line Example	Total Idle Time Initial [min]	Total Idle Time Optimal [min]	Shift Length Initial [min]	Shift Length Optimal [min]	Reduction of Total Idle Time [min]	Reduction of Shift Length [min]
1	1611	1519	727	722	92	5
2	1175	1063	570	570	112	0

The mean computational time (500 iterations) for the optimization of the two investigated production lines was 1.065 s and 0.878 s respectively.

Although both analyzed production lines are used in this (initial) setup for a long time and have repeatedly been enhanced empirically, there was an improvement possible coming from the optimization approach.

On production line one the total idle time could be reduced by 92 minutes (or 5.7%) by changing the product sequence. Furthermore the total runtime of the line could be reduced by 5 minutes. Focusing on the oven's utilization, the gap present in the former utilization could be closed (see Figure 7).

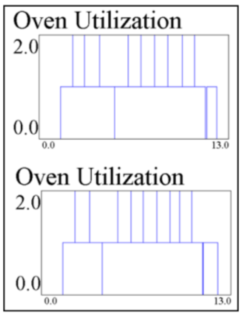

Figure 7: ARENA Plot of Oven Utilization on Production Line One before (top) and after Optimization (below)

The utilization of the other capacity limited stages is illustrated in Figure 8. Although the plots seem only slightly different the changes in the sequence result in the aforementioned reduction of the total idle time.

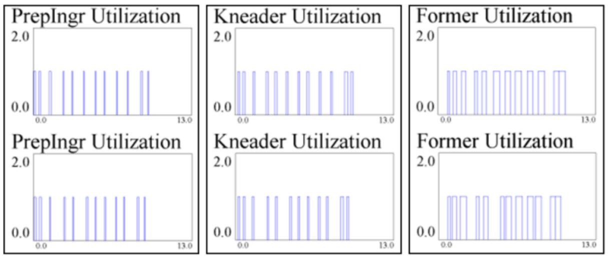

Figure 8: ARENA Plot of Utilization of Stages One, Two and Four on Production Line One before (top) and after Optimization (below)

On production line two the total idle time of the used machines could also be reduced significantly by 112 minutes (or 9.5%), although the total runtime of the production line did not change. Since this line was scheduled with special respect to the oven utilization there were no gaps in its utilization by running the initial product sequence. This status was preserved after optimization (see Figure 9).

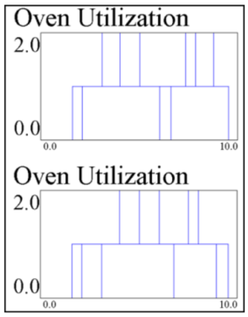

Figure 9: ARENA Plot of Oven Utilization on Production Line Two before (top) and after Optimization (below)

On this line the changes in machine utilization mainly appear in the previous stages (as shown in Figure 10).

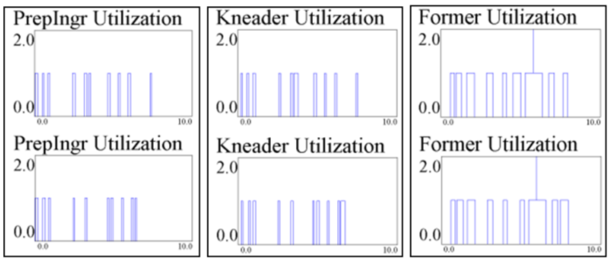

Figure 10: ARENA Plot of Utilization of Stages One Two and Four on Production Line Two before (top) and after Optimization (below)

4. CONCLUSION

The results obtained in the optimization of the two presented bakery production lines show the high potential that the use of numerical methods in general and of PSO in special has to improve the efficiency of baking companies. Especially the optimization of these two production lines that are used for several years in the presented setup and thought of as already optimal underlines the advantages process analysis with numerical methods can provide.

This potential is even higher if the presented PSO method is used as a decision support in the planning of new setups because it provides a fast and reliable possibility to find optimal schedules.

Since the implementation of PSO is easy and the modelling of production environments can be modified to match special product requirements, this method is suitable not only for bakery production but also for other time sensitive products as can often be found in other food industry branches.

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AUTHORS BIOGRAPHIES

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