INTERNATIONAL DESIGN CONFERENCE - DESIGN 2016
Dubrovnik - Croatia, May 16 - 19, 2016.

DESIGN OF A SELF-OPTIMISING PRODUCTION CONTROL SYSTEM

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Keywords: self optimizing systems, manufacturing, complex systems, systems engineering (SE)

1. Introduction and problem analysis

Product life-cycles nowadays become shorter, market volatility rises and cost pressure on companies increases. Manufacturing companies are more than ever exposed to global competition [Brecher et al. 2011]. Flexibility of production systems becomes steadily more important. This is due to the fact that companies increasingly see the need to respond to specific customer requests in order to be successful in the market [Wiendahl et al. 2014]. The development of products and production systems nowadays is mostly sequential and takes place separately in the various departments, which leads to restricted exchange of information. But the success of product engineering is set in the early stages of the development process [Gausemeier et al. 2012]. Futhermore, developing high-quality, complex products and the associated production systems successfully requires sound analyses and appropriate development tools. For this a holistic view of the development process is required. This implies the need for an integrative development of the product and the associated production system [Gausemeier et al. 2010]. The issue of restricted exchange of development informations is later reflected in the production planning. Accordingly, a study of the Fraunhofer Institute IAO documents that approximately two-thirds of the companies asked have very high, short-term control efforts [Spath et al. 2013]. Increasing use of software in the design of systems shall alleviate the problem. The paradigm of self-optimisation is a promising approach in encountering the control efforts and in realising an intelligent production control. A part of the field of artificial intelligence deals with attempts to implement such a control system. The aspired production control can react independently on changed orders. It can recognise and analyse system faults and deduce an appropriate response. According to Gausemeier, self-optimasation (SO) of a technical system is "the endogenous adjustment of the system's objectives as the result of changing influences and the resulting autonomous adjustment of parameters and if necessary the structure and thus the behaviour of this system" [Gausemeier et al. 2014]. The SO-process consists of the three recurring elements "analysis of the stituation", "determination of the system objectives" and "adaptation of the system behaviour." Nowadays production control systems can react to already known situations with predefined responses. However, the handling of unknown faults in the production system or changing restrictions are still problematic. Furthermore the system faces the challenge to know a lot about the current situation of the production system [Permin et al. 2016]. Completely, self-optimising production control systems (SOPC), which adjust their behaviour to changing conditions and learn from prior situations are still a vision. The basic structure and an approach to develop such a system was presented in [Mittag et al. 2014]. Lee and Liu also present architectures for the implementation of cyber physical systems in the field of production [Lee et al. 2014, 2015]. Both approches focus a generic architecture of a control system but not a specific implementaion of an optimiser.

Beside throughput maximisation other objectives such as energy cost or delivery delays minimsation have to be considered. The algorithm shall be able to find a solution in any production system. Already identified and stored reaction strategies to certain incidents shall be taken into account while looking for a solution. Newly generated solutions have to be classified and stored for potential reuse.
Key element of this work is a structural model, which describes the phases of the design by means of the SO-process. It describes which aspects are needed and how they are coherently implemented in order to design a SOPC. The system is described with the help of a laboratory project in which a contract manufacturer produces different types of flashlights and faces disturbances in his production system. The situation has been realised in a simulation model using a material flow simulation tool. With the help of this prototypical implementation the feasibility was validated.

2. Structure of the self-optimising production control system

The three phases of SO serve as the structure of the control system and as the division of the following chapters. Referring e.g. to the approach of Park the following can be considered as an explicit definition of the self-optimising control system within the presented general structure [Park 2013]. The first phase is the analysis of the situation with possible workflows of the manufacturing process for the current situation as the main result. The second phase is the definition of the system objectives. In this step, the production programme is optimised in regard to the various objectives. Result is one or several pareto-optimal production plans for the current production stituation [Gausemeier et al. 2014]. After a system external validation of the result, the phase adaption of the system behavior has to be conducted. The adjusted production programme and production system are the result of the third phase. This in turn is the input of the recurring first phase analysis of the current situation. Figure 1 shows the input data and milestones of the design. The phases are described in the following chapters.

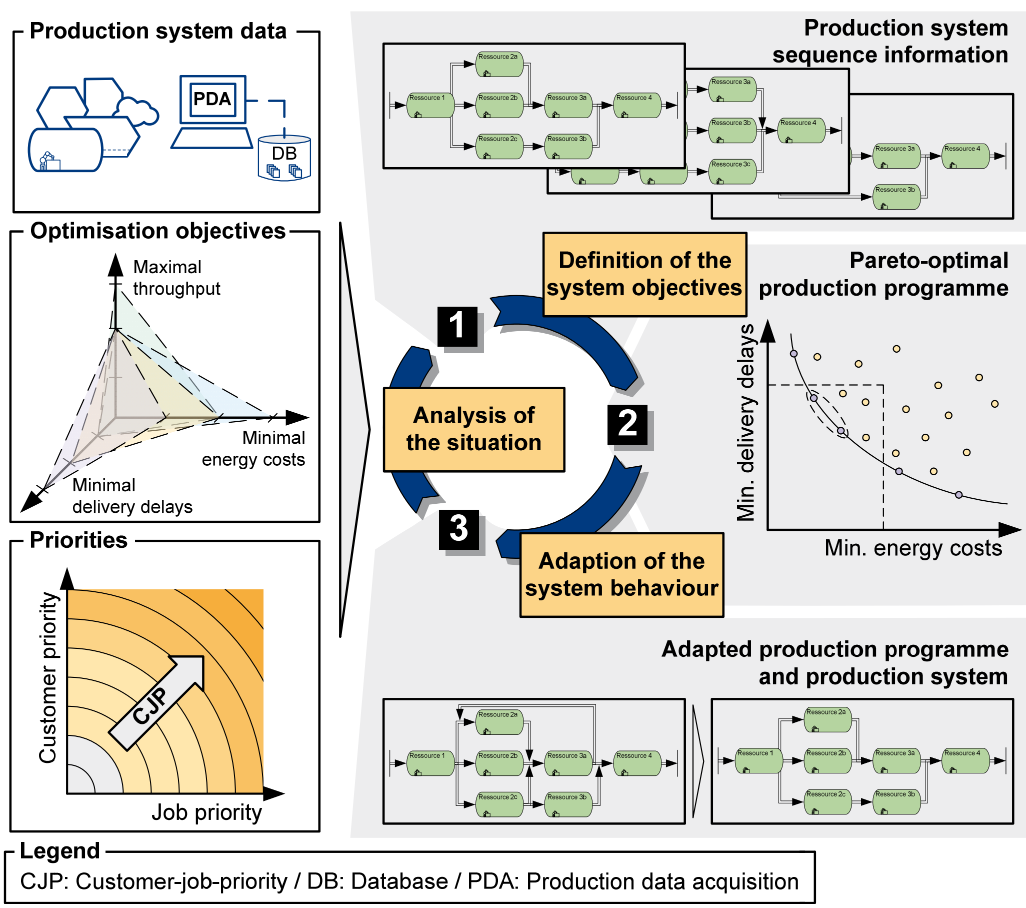


Figure 1. Structure of the self-optimising production control system

2.1 Analysis of the situation (phase 1)

The first phase of the SOPC is the analysis of the current situation. The input consists of three components. The first component is the basic information about the production system. This covers processes, resources and the behaviour of the production system and the production programme. For documenting most of the information, the cross-domain specification technique CONSENS is used according to [Gausemeier et al. 2010]. Eversheim divides the production planning into the four categories: new planning, adaption planning, variation planning and repetitvie planning [Eversheim 1997]. The documentation of the production system and the subsequent process is not restricted to one of these categories. This implies the new-, and re-design of Products. The production data aquisition is used to supervise the operational data. It applies to the initial documentation of the real system as well as to the monitoring of the system behaviour after the execution of the entire SO-process. Moreover, the objectives of the production have to be determined. They serve as the objectives of the optimisation. Finally, the orders have be prioritised. A customer-job-priority has been developed for this purpose. The detailed description of this information is depicted in the following chapters.

2.1.1 Objective of the production

Central component of the input data are the optimisation objectives. They are indispensable to define a systems outcome and hence to adapt the system in order to improve it. Wiendahl talks about the polylemma of the production [Wiendahl 2014]. The sub-objectives performance, cycle time, total cost and delivery delay represent conflicting objectives. The inventory is the explanatory variable in this context. Given a disturbance in the production system, the objectives throughput, delivery delays and energy costs are considered as the most important factors. Thus, these three objectives are pursued in the following. For an exemplarily implementation, the three sub-objectives are scored on a scale from one to three according to their importance. Three represents the value of the highest priority, whereas one represents the value of the lowest priority. The values of the priorities delivery delay/lateness and energy costs have to be determiend by the production planner. The priority throughput is determined implicitly. It has a negative correlation with the two other objectives.
Different use cases are imaginable for the combination of priorities. To describe the objectives of the production, only the priorities delivery delays (DD) and energy costs (E) have to be specified. If e.g. a producer of mass products without constraints in sales quantity is looked at, the combination DD:1 - E:1 is to be regarded as meaningful. In this case, the maximisation of the throughput is the overarching objective. For a contract manufacturer with an undistrubed production system, reasonable objectives are DD:2 - E:2 or DD:3 - E:3. This ensures that orders are completed on time. Additionally, energy costs will be considered and minimised. If the production system of a contract manufacturer is disturbed, the objective DD:3 - E:1 is preferable. By this means, the energy costs are less prioritised compared to the previous examples. This leads to an increase in throughput. The main objective in this scenario is the minimisation of lateness. Figure 2 shows the objectives of the production.

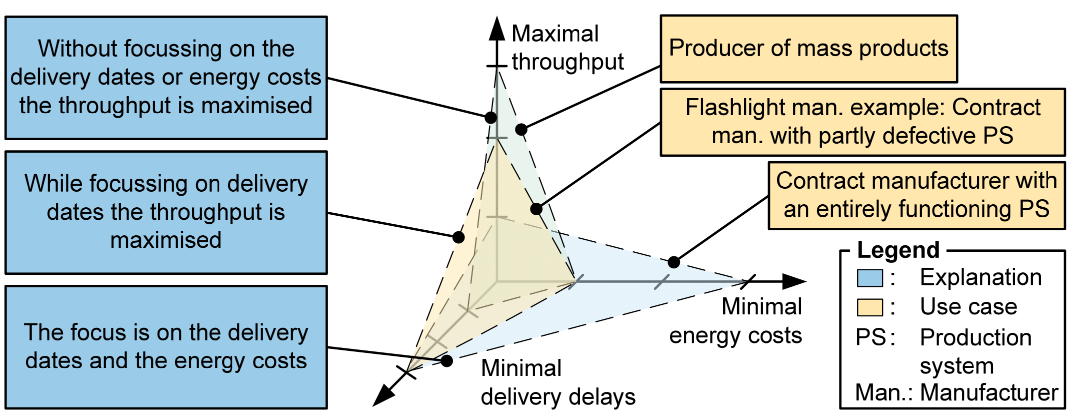
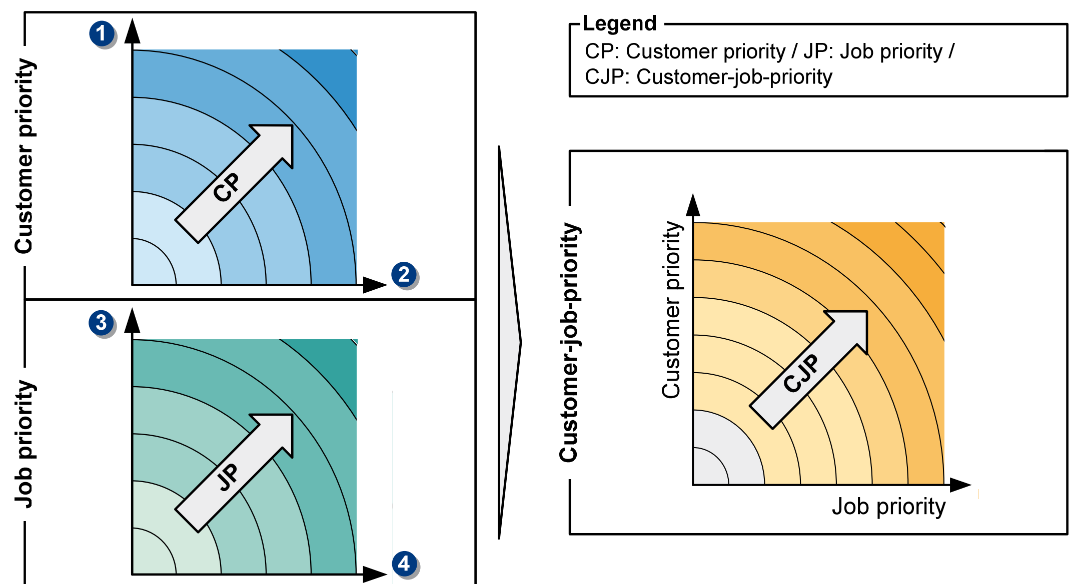


Figure 2. Objectives of the Production Control System

According to Nebl a holistic approach to a problem requires bringing together the sub-objectives [Nebl 2007]. Under certain assumptions and restrictions, the mentioned sub-objectives can be merged to the single objective of minimising costs. Restrictions are e.g. the practicability of the production plan or the adherence to a certain quality level. It should be mentioned that one has to keep in mind strategic aspects as well as monetary aspects while managing such a system.
For cost minimisation being able to represent the only objective, different quantifiable information must be given. The most obvious parts are the availability of energy, work and other costs. Possible penalties for late deliveries have to be known for each job. Non-monetary negative side effects of a late delivery, such as an image damage, are not considered in this work. Furthermore, the assumption is made that any surplus product can be sold at a predefined price. If this is not the case, the price is set to zero. By this means, additional goods will not create any value. This provides the basis for comparing the quality of production plans in an absolute manner. In a scenario where a company produces goods partially to stock and partially to order the preferable ratio can be determined. It can be assessed whether it is better to disregard certain orders in favour of an overall increased outcome.

2.1.2 Customer-job-priority for the prioritisation of orders

In order to implement the objectives of the production it is indispensable to prioritise orders. This also applies for establishing a sequence of orders in general. Therefore, an order individual prioritisation is needed. In the situation of a disturbance, it may be impossible to complete all jobs in the planning period. Alternatively, it may be the case that the production programme can only be completed with major additional costs. This requires special attention to the prioritisation of production orders. In doing so, the significance of the production order itself as well as the customer's significance have to be conisdered. For this reason, the customer-job-priority (CJP) is introduced (Figure 3).



1 Customer attractiveness	2 Relative customer importance	3 Operational order relevance	4 Strategic order relevance
▪ Customer’s turnover ▪ Development of customer’s turnover	▪ Share of one‘s current business ▪ Share of one’s future business	▪ Order volume ▪ Contractual penalties	▪ Assessment of pot. follow-up orders ▪ Alignment to product strategy

Figure 3. Defining the Customer-Job-Priority for the prioritisation of orders

The CJP is determined with the help of a portfolio approach. The customer priority (1) and the order priority (2) are determined independently at first. Afterwards they are combined to the CJP.

(1) The customer priority is determined regardless of the current order situation. Since the contracts are eventually made with the customers and change over time, the customer priorities have to be revised at regular intervals. The value of the customer priority arises from the customer attractiveness and the relative customer importance. To determine the customer attractiveness the customer's turnover and the development of the customer's turnover are used. The values are independent from one's own business and any relationships with the customer and represents the general potential of making business with the customer. This is generally higher for large businesses since they can award more and greater orders in terms of the monetary volume. The relative customer importance documents how the regarded company uses this potential to make business. Two aspects are used to define the relative customer importance. The first one is the share of the customer of the current business. The second one is the share of the customer of one's own business in the future. To assign values, the customers are categorised. Like it is mentioned in [Albers et al. 2005] or [Gansser et al. 2015], it is important to include qualtitative aspects in the assesment of the share of one's business in the future.
(2) The order priority is determined depending on the current production situation. It is derived from the operational and strategic order relevance. The operational order relevance considers exclusively monetary aspects. It results from the order volume and the contractual penalties. Like this, bigger orders can be prioritised higher. Likewise can orders be prioritised higher which would result in significant contractual penalties if they are not completed in time. This is of particular relevance in a disturbed production system. The strategic order relevance also results from two factors. One is the assessment of potential follow-up orders. The second one is the order's accordance to the companie's product strategy. Like this, orders can be prioritised higher which seem to be rewarding in terms of potential follow-up orders. Additionally, it is considered that the orders match the strategy of the company and a promotion of exotic products which does not represent the core business is avoided.
The CJP results in a scale of one to ten. The values define ten classes, which imply acceptable deviations of the original delivery dates. A CJP considered delivery date is calculated for each order with this information. The newly calculated delivery dates replace the original ones in the case that not all orders can be completed within the planning period. Since the production programme is sorted by the CJP considered delivery date, it can be assured that very important orders are manufactured earlier than less important ones. This is based on the assumption that the production system is not oversized for the current order situation and thus important orders cannot easily be produced to stock.

2.1.3 Work plans for the sequence planning of products

To change a production programme in a structured way, it is essential to be able to handle products and their work sequences. Within the SOPC, work plans represent the basis for a structured rescheduling and hence for the optimisation. A work plan constitutes a possible route of the product through the system. If a product can be processed with alternative resources, it is presented with different work plans. In the case of a resource failure, the work plans including the defective resource are disregarded. Furthermore, while regarding alternative objectives, an appropriate work plan can be selected. Figure 4 shows extracts of alternative work plans from the flashlight manufacturer.
The work plans are generated automatically by the simulation model. The basis for this are the product-processes-matrix (PPM) and the processes-resources-matrix (PRM). The PPM defines which processes are required to manufacture a product. The processing times are included here. Different quality levels of processes are represented as separate processes. The PRM defines, with which resources a process can be executed alternatively. This allows the generation of all combinations of work plans.
Regardless of the optimisation objectives, the work plans are initially sorted by the cycle time. The work plans with the shortest cycle times are initially the preferred ones. Later on, the work plans of the products are changed for the following simulation runs. This is done with regard to the optimisation objectives. To reduce the complexity of the control, it is useful to bundle resources. A work system represents the combination of a material buffer and all resources of the same type. Within a work system, a local allocation logic is applied where the buffers provide the resources with the material. While only pursuing throughput maximisation as the only objective, the resources with the lowest quality levels are first provided with material. By this means the resources with a higher quality level are kept vacant in case there is a job which needs such a high quality level.

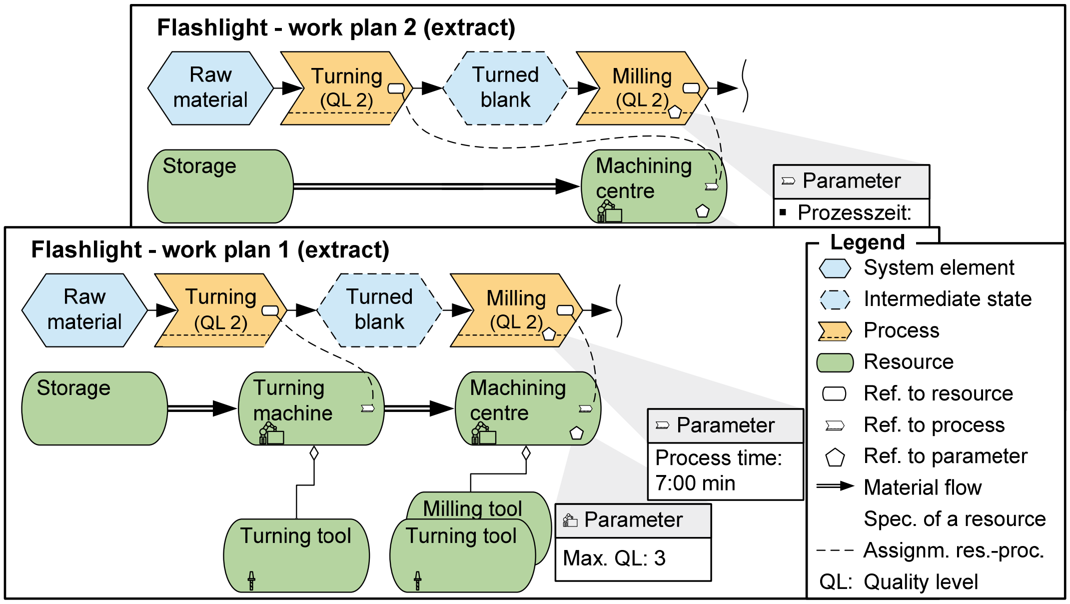


Figure 4. Work plans for the definition of sequence information

In the flashlight production, represented in Figure 4, the raw material can first be turned on the turning machine. Then it is milled on the machining centre. Finally, the product is assembled on a manual workplace. Work plan two in contrast defines that the product is turned and milled on the machining centre. Afterwards, the product is assembled on the manual workplace. For every resource the maximum possible quality level is defined to query whether the corresponding process can be executed on the resource. If a product requires a higher quality level than a certain resource, the corresponding work plans will not be considered. If a resource turns out to be defective, the resource's quality level can easily be set to the lowest level, which excludes it from all work plans.

2.2 Definition of the system objectives (phase 2)

The starting point of the simulation is a list of orders. These are sorted by the CJP considered delivery date. The list is transferred to a production programme and iteratively optimised.

2.2.1 Structure of the simulation

The idea of the SOPC is a simulation process which initially analyses the production programme, then optimises it and then invokes itself. At the beginning, the master and order data are entered as the input for the simulation. Then the optimisation objectives are defined.

The orders are then transferred to an initial, arbitrary production programme. This initial production programme is simulated to get a timeline for optimisation. This means that the simulation calculates at what points in time the products are processed on which resources. This information is necessary for the following optimisation steps. If the sole purpose is maximising throughput, the underlying idea of optimisation is a levelling of the workload. While pursuing the multiobjective optimisation, other factors are taken into account when adjusting the production programme.

At the end of a simulation run, the convergence of the fitness function is evaluated. If the fitness function remains within a tolerance range over a certain period, it is ascertained that an optimum is found. This implies that the global nature of the solution cannot be guaranteed. In order to encounter this, the observation period of convergence is enlarged and another validation step is conducted. This analyses the production during a simulation run and adapts it if necessary.

If the convergence of the objective value is not given, the simulation invokes itself and performs the optimization steps again. When the value of the fitness function converges the simulation is terminated. The optimised production programme is classified and stored.

2.2.2 Steps of the optimisation process

The optimisation process can be divided into three steps, each providing an improvement for the next simulation. The last step is repeated as long as the result is improving. The steps are the same in an undisturbed as in an disturbed production system. The difference is reflected in the work plans.

(1) The orders have to be created. The production programme is deduced from this and optimised based on statically calculated capacity data. In doing so the production programme is analysed as a whole. The process times of all orders for each resource are summed up. This is done with the help of the work plans. The value is compared with the available time of each resource. Knowing which work plan uses which recource how much, a reasonable overall distribution of work plans is deduced. Then the production programme is simulated and divided into time intervals.

(2) The next step is to optimise the production plan using the defined time intervals. This represents the same optimisation step on a more detailed level. It is to mention that the number of products in a time interval can change while changing the work plans and the sequence.

(3) The optimisation beginning in the third simulation run is conducted multiple times. The analysis is based on an analysis of the work systems during a simulation run. The goal is a leveled utilsation of work systems. This is tracked with the help of the buffer stocks. For the work systems, an aspired (μ) buffer stock with tolerances (α) is defined. This is based on the idea, that a too low buffer stock may result in a material cut-off of the following resources, on the one hand. This results into idle time. On the other hand, a buffer stock which is to high would lead to a blocking of the previous resources.

Based on this analysis, the production programme will be adjusted and then simulated. The changes concern the distribution of work plans and the processing sequence. At first, the time interval is identified, in which a work system is mostly utilised. Then the interval is identified, in which the work system is utilised the least. Afterwards, orders of the interval of the maximum use are moved to the interval of the minimum use. This is repeated until the fitness function converges.

Steps one and two improve the production programme exclusively in terms of the throughput. In the third step, various objectives may be taken into account. This is described in section 2.2.3. The reason for the two steps is the faster convergence of the objective value.

2.2.3 Implementation of the multiobjective optimisation

The basis of the optimisation in terms of energy costs is the iterative levelling of the utilisation of the work systems. Furthermore, an allocation logic within the work systems is provided, which states that the resources with the lowest energy consumption are provided with products the first.

If energy efficiency gets prioritised higher, the utilisation of work systems is lowered by means of the aspired buffer stocks. This is done on several levels. The levels are linked to the energy efficiency classes of the resources. The higher the energy consumption of a work system is, the less it will be utilised. Thus, less products are provided to the work systems. The result is a lower utilisation of the most expensive resources within the work system and therefore savings in energy costs.

The levels of the aspired stocks have to be defined individually for the work systems. Like this, the energy consumption is considered locally and throughout the production system. Energy efficient resources are prioritised within a work system and so are energy efficient work systems within the whole production system. The values of the aspired buffer stocks are specific for each production system in general. In determining the aspired buffer stocks, the processing time of the products are in the focus. If the range of the product's processing times is very large, the processing times are used to define the aspired buffer stock level instead of the number of products. Figure 5 shows the approach. The production system of a flashlight manufacturer is shown on the left side. It has three work systems. The first one consists of turning machines which have a medium energy consumption. The second work system, consisting of milling machines, has a high energy consumption. Due to its lower energy costs, the buffer stocks of the first work system is higher and thus receives more material. It implies that if material can be turned in work system 1 or in work system 2, the first one will be the prefered one. This results in a lower utilization of the expensive work systems. Additionally the expensive resources are less utilized within a work system.

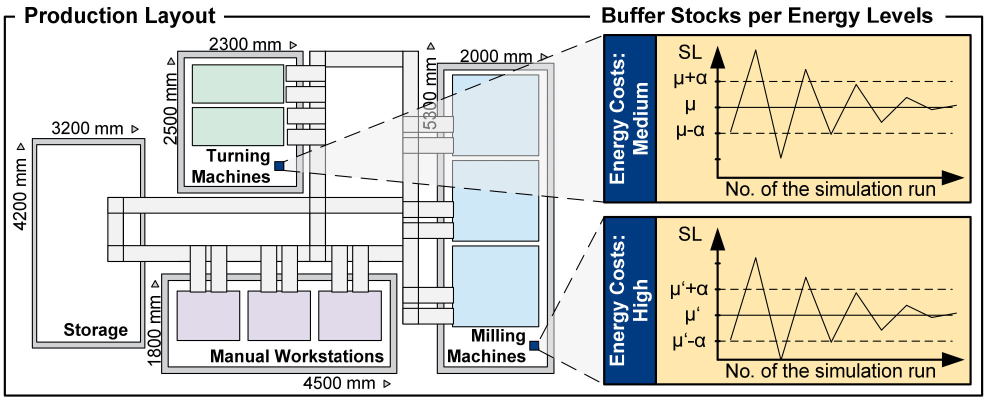


Figure 5. Realisation of different energy priorities

The prioritisation of the delivery delays is taken into account in the change of the job sequence. Within the iterative optimisation of the production programme, jobs are shifted successively in the production programme. Initially, the time interval in the current production programme is identified, in which a work system is utilised most. Then, the interval is identified, in which the work system is utilised at least. Afterwards, the products are shifted from one to the other. Now, while prioritising the delivery delays, the temporal region in which the products can be moved gets restricted. Nevertheless, the process of shifting remains basically the same. There, the intervall utilised the most is identified at first. Then a product individual range of time intervals is calculated. Within this range the interval utilised the least is identified and the products are moved.

By limiting the range, it is ensured that jobs will not be moved from the beginning to the end of the production programme and vice versa. The basis for this is that the production programme was arranged after the CJP considered delivery date at the beginning. This implies that the products are in the correct order in terms of the relevant deadlines. Very important orders can be preferred with the help of the CJP considered delivery date. These due dates took into account a maximum tolerable deviation from the original delivery dates. Having a very high CJP value, the acceptable deviation form the due date is very low. The order individual search area for swapping is calculated with Equation 1. This considers the priority of the lateness and the priority of the individual order. The higher the lateness and/or the CJP is, the smaller is the search area for swapping a product. This implies that the product remains at its predetermined place in the production plan.

$$Search\ area\ for\ swapping = \frac{Number\ of\ time\ intervals\ in\ the\ planning\ period}{(CJP) * (Priority\ of\ the\ delivery\ delay)} \quad (1)$$

2.2.4 Determination of the pareto-optimal solutions

The definition of the production objectives is the basis for the evaluation of the results. These can only take monetary aspects into account. If strategic aspects are also considered with the CJP, the solution of the optimisation may not be explicit. The convergence criterion is in either way the throughput. The different objectives of the production will be considered within the simulation itself.

If different objectives are pursued, those scales are ordinal. This implies that there is no "optimal" trade-off. Because of this, three production programmes are proposed in the evaluation of the optimisation. The solutions are the most cost-effective production programme, the one with the most throughput and the one with the least lateness of deliveries. The programme with the lowest energy costs is redundant, since the total cost-effective production plan is included. The number of proposed solutions may rise, if additional sub-objectives are included. The proposal of a solution implies that the solution creates positive benefit. If there is a disturbance in the production system, this does not necessarily mean that the production programme has to be changed. If e.g. the disturbance is quickly fixed, it may be better to maintain the current production programme and to wait until the fault is repaired. It has to be considered that orders may have to be canceled if the production plan is changed.

To assess the usefulness of changing the production plan because of a disturbance, the repair time has to be estimated. Since this can vary greatly, an expert has to be consulted. The more accurate this

assessment is, the better is the estimation of the benefit of a setup change. Simultaneously, the simulation model is used to simulate the production system. This is done for the disturbed system as it is. Then it is optimised with the process described before. It is deduced how many more products can be produced with the system when changing the production plan. Since the old production plan included the defective resource, a new production plan will generally be able to produce more output.
The difference in the system output is the increase in value of the change of a production plan. The objective value may be specified as either throughput or as the total cost of the production programme. The value is converted to products per hour and finally to work per minutes. These work minutes per hour can be considered as the increase of value per hour of a changeover. When assuming that the change is made after an increasing number of hours, the benefit of the change is decreasing linearly.
Against the increase in value of the changeover, the depreciation of a changeover is illustrated. This is the lost time due to a change in the production programme after the mentioned time period. The lost time is the sum of the set-up times, etc. of orders which have to be canceled due to the changeover. This results normally in a non-continuous curve, because jobs are gradually completed when the production programme would not be converted. In this approach it is assumed that following new orders enter the system in the optimised sequence and therefore no additional set-up time would be needed while conducting the changeover. The difference of the two values represent the benefit of the change after different periods of time. The value has to be maximised. This determines after how many hours the production programme should be changed. With this approach it is implicitly considered that changing a flow shop production is more difficult than changing a job shop production, since the set-up times are larger. If the objective is not only maximising throughput, it is reflected in the simulation itself and the adapted fitness function. It is still the throughput of the rearranged production programme which is compared to the original one.

2.3 Adaptation of the system behavior (phase 3)

Depending on the production objectives, the SOPC proposes one or several pareto-optimal production programmes (Figure 6). Only production programmes with a positive benefit will be considered.

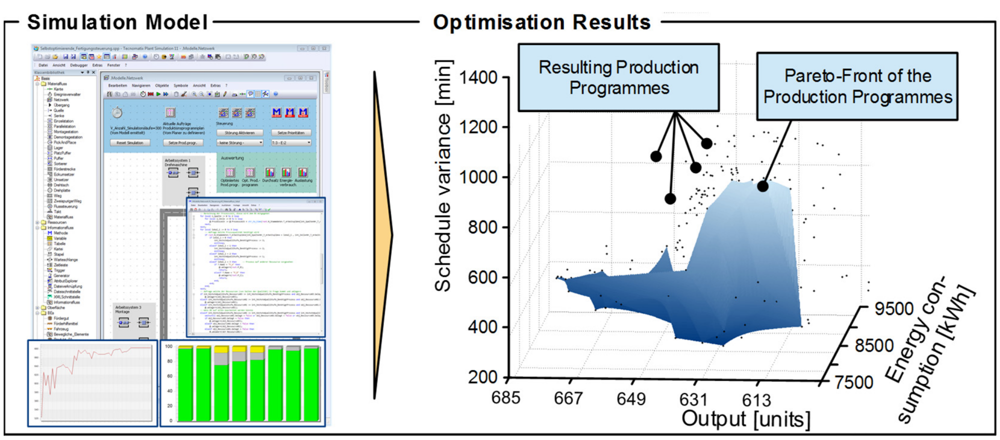


Figure 6. Realisation and results of the self-optimising production control system

To compare the production programmes, solely the characteristics of the objectives are relevant. These characteristics are the coordinates of the points in Figure 6. The optimisation programme allows a dynamic change of one's preferences within the multiple objectives. Not only are the outcomes easliy comparable, but also can the production system change its setting quickly. The work schedules, underlying each production programme, are the key result of optimisation. These are shown in a flow chart like a gantt chart. Which of the production programmes is to be choosen, has to be decided by the production planner. Afterwards, the result needs to be validated by the production planner. If changes are made, the production programme may be simulated again. Finally, it will be saved as a reaction strategy for this incident in the production system control.

3. Conclusion and outlook

In this work, the design of a self-optimising production control was presented. It describes the structure of the system independent of a specific production system. The system manages even unexpected situations not taken into account by planners, such as disturbances or rush jobs. It is able to independently optimise a production programme. In the development was considered that the objectives of the production can vary greatly. In this work, the objectives throughput, delivery delays and energy efficiency are considered exemplary. However, the presented design allows an expansion of these objectives. To ensure that important jobs are completed even in a partly defective production system, orders can be prioritised differently. The customer-job-priority was introduced for this purpose. As part of this work, the self-optimising production control has been implemented with a material flow tool and tested on a laboratory project. The central element of further work represents the adaptation and validation of the production control in a real size production system. Moreover, the objectives of the production are to be detailed to a comprehensive target system in further work.

Acknowledgment

The work in this paper is fundetd by the German Federal Ministry of Education and Research (BMBF) within the Leading-Edge Cluster "Intelligent Technical Systems OstWestfalen-Lippe" (it's OWL) as well as the Collaborative Research Centre (CRC) 614, which is kindly supported by the German Research Foundation (DFG). The authors are responsible for the contents of this publication.

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