Dear Colleagues,


On behalf of the CIRP CMS 2013 Organising Committee, we would like to invite you to read and follow the papers presented at the 46th CIRP Conference on Manufacturing Systems, held in Setúbal, Portugal, on May 29th-30th, 2013, with the theme of “Economic Development and Wealth through Globally Competitive Manufacturing Systems”.

The 46th CIRP Conference on Manufacturing Systems (CIRP CMS 2013) was an international forum of researchers and industrialists, from all over the world, offering the opportunity to all the participants to be actively involved in technical and scientific discussions on the manufacturing systems’ trends and their contribution for sustainability and development of manufacturing companies and of societies worldwide.

The current situation in Europe and the world highlights the important role of manufacturing activities for societies, in contributing to their sustainable development, particularly with jobs, human realization and wealth. For the manufacturing company’s competitiveness the key issues to be met are the socio-economic challenges, knowledge development and application, in all aspects of the manufacturing systems design and management.

Organizing this year the CIRP Conference on Manufacturing Systems in Setúbal, Portugal, we created a favourable environment to share and discuss new ideas, launch initiatives for new projects or new businesses, which brought together the scientific and the business communities. We also contributed to stimulate technical and scientific discussions on manufacturing systems and their implications for industry, to provide an international platform for the exchange of the latest ideas and developments on manufacturing systems, to act as a driver for new research themes and international networking and to promote the development of collaborative networks to support the involvement of manufacturing systems and their global competitiveness.

The goal of the 46th CIRP CMS 2013 was to review and discuss the advances, research results and other improvements in the area of manufacturing systems, taking different perspectives and innovative approaches and envisioning future trends. These reviews and discussions covered a wide variety of research topics such as Supply chain and global production management, Production networks, Intelligent, adaptive and e-manufacturing, Digital manufacturing, Factory and production planning, Design and application of production systems, Flexible and reconfigurable manufacturing systems / Agile manufacturing, Sustainable production, recycling and remanufacturing, Energy-efficient processes and systems, Process modelling and process planning, Simulation and optimization of manufacturing systems, Micro manufacturing, Nano manufacturing, Novel processes and machinery, Life cycle management, Concurrent engineering, Industrial product service systems (IPS2), Production systems evolutions (SPECIES), Quality and maintenance management, Knowledge and data management in production and logistics, Beyond lean and Education in learning factories.
We would like to acknowledge the contribution of all our authors who participated in the 46th CIRP conference on Manufacturing Systems with the submission of such high quality papers. We formally thank all those who assisted in any way with the preparation and delivery of CMS2013, including the distinguished members of the International Scientific Committee, Local Organising Committee and Industrial Committee. We would like to especially acknowledge the major contribution of our referees, whose valuable comments improved the quality of papers and consequently enhanced the academic quality of this Edition of Procedia CIRP.

Finally, we are deeply grateful to the sponsors of CMS2013, whose financial support was essential for the success of the meeting and the outcomes obtained, such as the present document, in particular Bosch Termotecnologia SA, SAGE Portugal and Volkswagen Autoeuropa.

Pedro Filipe do Carmo Cunha
Chairman of 46th CIRP Conference on Manufacturing Systems

President of Directors of CENI – Centro de Integração de Inovação de Processos Assoc.I&D
Professor Adjunto at Escola Superior de Tecnologia / Instituto Politécnico de Setúbal
Modelling of flexibility costs in a decision support system for mid-term capacity planning

Lukas Lingitz\textsuperscript{a,}\textsuperscript{*}, Christian Morawetz\textsuperscript{a}, Dariush Tavaghoo Gigloob\textsuperscript{b}, Stefan Minner\textsuperscript{b}, Wilfried Sihn\textsuperscript{a}

\textsuperscript{a}Fraunhofer Austria Research GmbH - Division Production and Logistics Management, Theresianumgasse 7, Vienna 1040, Austria
\textsuperscript{b}LS Logistics & SCM, TUM School of Management, Arcisstraße 21, 80333 Munich, Germany

\textsuperscript{*} Lukas Lingitz. Tel.: +43 676 888 616 15; fax: +43 1 504 69 06; E-mail address: lukas.lingitz@fraunhofer.at

Abstract

Nowadays manufacturing companies are coerced to become more flexible to adapt their internal processes quickly and economically to the volatile external situations. In this paper, we develop a cost model with respect to the capacity envelope concept. Generic flexibility measures are used and described by numerous influence factors and constraints. Furthermore, the cost model will be demonstrated as a mixed-integer linear model and is finally integrated in a decision support system for mid-term production planning. The resulting problem can be solved with commonly available standard solvers. Finally, we will show numerical results from practice.

Keywords: aggregate production planning; capacity flexibility; production flexibility; mid-term capacity planning; work-time account

1. Introduction

Over the past years, companies had to face more fluctuations in product demand.\ [1]\ In the future, these highly volatile environments are more likely to increase than to decrease. Level, chase and escalation are strategies to cope with fluctuations in demand. Leveling decouples production and demand. Production volume and capacity are held constant over the time and finished goods inventory is used to level capacity requirements. The chase strategy implies continuous adaptation of production capacity on the customer’s demand. A combination of both is called escalation. The production capacity is increased or decreased if necessary. [2] Whilst levelling creates high capital costs for finished goods and the risk of high mark-downs if the sales forecast predicted higher demands, the chase strategy causes high costs for continuous capacity adaptation, if this strategy is viable at all. The hybrid escalation strategy balances the above cost trade-off.

Several additional reasons hinder these strategies from existing in pure form in industrial application; for example warehousing restrictions such as capacity or shelf life of products or limited machining capacities.

In mid-term capacity planning, a production plan based on the internal production capacity is generated in order to meet the dynamic forecasted demand. This planning step is called aggregate production planning (APP) [3]. In practice, it is often done manually and iteratively by a planner.

Typical optimisation models for APP often use one or a combination of the following strategies by minimizing the total costs over a time horizon [3]:
- increase and decrease of the production rate through overtime and undertime,
- adjusting the workforce through hiring and laying off employees,
- smoothing and balancing by means of finished goods inventory and
- subcontracting/outsourcing parts of the production volume.

In practice, there are numerous capacity adaption measures. 20 generic capacity measures for example, have been listed by Morawetz [4]
Although numerous adaption measurers are well known in the industrial application, their effects on the production cost are often not treated adequately within the planning process. Therefore, we propose a decision support model using different measures in particular for modern industrial companies in high wage countries.

2. State of the art

Many contributions in the field of aggregate production planning dealt with the development of solution algorithms, whereas the proposed models hardly model the modern industrial environment realistically. Fahimnia proposes a model for aggregate production planning including overtime, adaption of the workforce level, outsourcing/subcontracting, and the deployment of inventory policies. Within the workforce model, the personnel is divided into experienced and new workers with different productivity levels. A continuous time production planning model solved by means of a hybrid algorithm is presented by Ganesh. Kumar solves a production planning model based on annual working hours. In these models the employment of different shift patterns is not considered.

The contribution of the model that is proposed in this paper is the implementation of different shift patterns including related shift-dependent maximum overtime and a work-time account model. In contrast to the mentioned models the workforce level in this contribution can only be adapted step-wise. This assumption regards the fact that the production rate of highly automated production facilities cannot be increased by hiring single workers but by hiring or firing workers to operate a station in another shift pattern.

Besides the literature on aggregate production planning, many authors deal with the challenges of adapting production capacity to customer demand in order to achieve flexibility. The core idea of the capacity envelope model is to adapt the capacity of a production system through the application of different capacity adaption measures. Each measure is described by numerous attributes such as minimal or maximal installation time, latency from the point when the decision is made to the time it is capacity-effective and the actual effect on the capacity level that can be achieved.

2.1. General approach for cost modelling

The determination of the cost parameters of an APP model is crucial for the results and is therefore discussed in this section.

A commonly used method for the cost calculation of cost objects in practice is the machine-hour rate calculation. This method is a based upon full cost calculation and therefore causes a deviation between the actual costs and the calculated costs whenever the actual working duration differs from the estimated working duration that builds the basis for the calculation. The calculation of a one and a two shift machine-hour rate causes also a deviation.

For marginal cost accounting or process-cost accounting standards and numerous recommendations exist. These are the reasons for the wide-spread application in practice. The linearisation of variable costs within these accounting models causes an unrealistic representation of these cost effects in internal corporate accounting and causes non optimal result when applied in decision making processes. The weakness of these costing systems can easily be demonstrated by means of labor costs. Piecework rate is dependent from the employment and therefore modeled correctly when included in the variable costs. Hourly-wage cannot be ascribed to the cost object. It is dependent from the provided capacity. For a short term, this capacity can be considered as fixed, but in a mid or long-term view the capacity level and according to this the related costs are variable.

Another model is the “relative direct costs and contribution margin accounting” system. It is rather a calculation system than an accounting model and provides only a mindset. The core idea is to define decision relevant reference objects and characterize the affected costs of this object.

Taking this mindset into account a modelling approach for the aggregate production planning was developed and will be presented in the next section.

3. Modelling Approach

In this section we will review common cost drivers for flexibility measures.

Like in common models we also divide costs into fixed and variable. Fixed costs are all costs that are not affected by use of flexibility measures. All costs that are affected by decision made on the strategic level, such as leasing of external warehouses or investments in
machinery and the associated time-dependent depreciation, can be considered as fixed for the APP model.

Costs that are affected by a capacity measure can be considered as variable. Within this group the costs have to be divided into proportional, step fixed, digressive and progressive.

In the following chapters the relevant costs and the cost drivers for particular flexibility measures will be discussed.

3.1. Overtime/Undertime or additional shift/closure days

In many production facilities, employees have flexible labour agreements based upon working-time accounts. This allows companies to distribute the total number of working hours irregularly over a specific reference period. The characteristics of such accounting systems depend on legal regulations, collective agreements and company agreements. These circumstances have a strong impact on the costs of overtime and undertime and will therefore be examined.

Generally, the weekly working hours can be adapted within predefined boundaries without the need to pay surcharges as long as the work-time account is balanced until the end of a certain period. Special regulations can allow a company to transfer a positive account balance as deposit into the next period. A negative account balance cannot be transferred to the next period and is set to zero.[15] Additionally, it is possible to exceed the upper limit by paying additional surcharges. The maximum available overtime per period is usually dependent from the work center calendar (weekends, holidays), the applied shift pattern and the legal boundaries for maximum work-time per day and week.

To cover the costs of overtime, undertime, additional shifts and closure days, a work-time account has to be implemented in the model. If the account reaches a limit, the model can either use extra shifts, which causes step-fixed costs, or single extra hours, which causes extra costs proportional to the needed capacity. The relevant costs are only those costs that differ from the costs on a normal working day, e.g., surcharges for the employees or differing cost rates for electricity.

3.2. Design of shift patterns

Shift patterns are usually used in highly automated production plants or assembly lines. Each work station in a production line has a limited capacity within a shift and requires a specified number of employees. In order to increase or decrease the total available capacity, work stations are run according to different shift patterns. Personnel costs at a work station are not affected by the production quantity, but by the provided operating time.

Therefore, the corresponding costs are not continuous but discrete, for example when changing from one shift pattern to the other. Costs for hiring or firing workers to change the shift pattern must be calculated and considered whenever the shift pattern changes.

3.3. Outsourcing

Outsourcing is one of the main flexibility measures. It usually depends on agreements between the company and its suppliers.

The costs for outsourcing are proportional to the number of sourced products. If outsourcing is done occasionally, extra costs for searching and acquiring a supplier have to be considered for each time a product is sourced. Besides this, companies use framework contract warehousing where the price per part and certain regulations about the volume are described.

3.4. The finished goods inventory

One of the most important flexibility measures to balance production volume is inventory. The holding costs are not only dependent from the value or volume of the stored goods, but also on the warehouse structure. Internal warehouses have fixed costs (e.g. building, maintenance, cleaning, personnel and internal transport) as well as variable costs (e.g. capital costs, insurance costs per stored unit). The relevant costs for external warehousing are usually the capital cost and the cost per unit for the storage area. For mid-term capacity planning it can be assumed, that the inventory level has little effect on the fixed costs and can therefore be neglected.

4. Model

In this section we present a mixed integer linear programming formulation. Let \( I \) denote the set of products \( i \in I \) and \( T \) the set of finite number of discrete time periods \( t \in T \). Demand is assumed to be deterministic and denoted by \( d_{it} \). We let \( F \) denote the set of plants \( f \in F \) and \( L_f \) the set of active production lines in every plant \( f \). Each plant \( f \) is capable of producing a set of certain products denoted by \( I(f) \).

Each product \( i \) has been assigned to production lines \( l \in L(i) \) where \( L(i) = \sum_{f \in F} L_f \) with a production capacity consumption of \( a_{it} \). Each production line \( l \) can be run on \( s \in S \) different shift patterns with cost of \( f_{CS_{ls}} \) in period \( t \). Overtime cost in production line \( l \) on shift pattern \( s \) in period \( t \) is denoted by \( f_{CO_{ls}} \). Changing a shift pattern in production line \( l \) causes cost of \( f_{CP} \). Let \( NC_{sl} \) and \( OC_{sl} \) denote the effective available working time and available overtime working for all production lines within plant \( f \) in period \( t \) on shift pattern \( s \) after extracting maintenance time, respectively. We assume a
warehouse within each plant $f$ with storage capacity of $W_f$ palettes. Let $h_i$ and $h_{fi}$ denote the quantity of product $i$ in one palette and inventory holding cost at warehouse of plant $f$ at the end of period $t$ respectively. For each product $i \in I$ we consider a minimum inventory level of $ss_i$ units. Let $uc_i$ and $UK_i$ denote the cost of outsourcing a unit of product $i$ and total outsourcing capacity for product $i$ in period $t$. It is also assumed that there is not any transportation cost among warehouses.

In order to integrate the working time account into the model, we require the following parameters: $of_i$ indicates a coefficient to calculate the supplemental times of overtime in plant $f$. Furthermore, let $om_{fi}$ denote the maximum vacation time that can be taken from the working time account in plant $f$ in one period. Finally, $ou_{fi}$ indicates the upper limit of a working time account in plant $f$. If the working time account in some production line within plant $f$ exceeds the upper limit at the end of the planning horizon, it is paid as supplemental wage $k_f$.

The decision variables are defined as follows:

- $x_{ilst}$: Quantity of product $i$ produced in production line $l$ on shift pattern $s$ in time period $t$
- $y_{ilst}$: Quantity of product $i$ produced during overtime in production line $l$ on shift pattern $s$ in time period $t$
- $z_{ilst}$: Quantity of product $i$ outsourced in period $t$
- $I_{ilst}$: Inventory of product $i$ in plant $f$ at the end of period $t$
- $e_{ilst}$: Quantity of product $i$ used from plant $f$ to fulfill demand in period $t$
- $of_{ilst}$: Indicator if production line $l$ runs on shift pattern $s$ in period $t$ ($-1$ otherwise ($0$))
- $os_{ilst}$: Indicator if overtime used in production line $l$ on shift pattern $s$ in period $t$ ($-1$ otherwise ($0$))
- $ob_{ilst}$: Indicator if there is a shift change in production line $l$ in period $t$ ($-1$ otherwise ($0$))
- $oi_{ilst}$: The total supplemental time gained by doing overtime in production line $l$ over planning horizon
- $ov_{ilst}$: Value of working account in production line $l$ at the end of period $t$
- $oh_{ilst}$: Vacation time used from the working account in production line $l$ in period $t$
- $oh_{ilst}$: Amount of working account paid as supplemental wage in production line $l$ at the end of period $t$

Subject to

$$
\sum_{i \in I} \sum_{f \in F} a_{if} x_{ilst} \leq NC_{sfi} \quad f \in F, l \in L_f, s \in S, t \in T \quad (2)
$$

$$
\sum_{i \in I} \sum_{f \in F} a_{if} y_{ilst} \leq OC_{sfi} \quad f \in F, l \in L_f, s \in S, t \in T \quad (3)
$$

$$
\sum_{i \in I} \sum_{f \in F} z_{ilst} \leq UK_i \quad 0 \leq i \leq I, \forall t \in T \quad (4)
$$

$$
I_{ilst} = I_{ilst-1} + x_{ilst} + y_{ilst} + z_{ilst} - e_{ilst} \quad i \in I, f \in F, l \in L_f \cap L(i), \forall t \in T \quad (5)
$$

$$
\sum_{f \in F} e_{ilst} = d_{ilst} \quad \forall i \in I, l \in L_f, t \in T \quad (6)
$$

$$
\sum_{f \in F} I_{ilst} \geq ss_i \quad \forall i \in I, l \in L_f, t \in T \quad (7)
$$

$$
\sum_{i \in I} \sum_{f \in F} \left( \frac{I_{ilst}}{h_i} \right) \leq W_f \quad f \in F, \forall t \in T \quad (8)
$$

$$
\sum_{i \in S} NC_{sfi} \cdot \phi_{ilst} - \sum_{i \in I} \sum_{f \in F} a_{if} x_{ilst} \geq om_{fi} - \beta_{hi} \cdot M \quad f \in F, l \in L_f, t \in T \quad (9)
$$

$$
\sum_{i \in I} \sum_{f \in F} \sum_{l \in L_f} \sum_{s \in S} a_{if} y_{ilst} \geq om_{fi} - \beta_{hi} \cdot M \quad f \in F, l \in L_f, t \in T \quad (10)
$$

$$
\sum_{i \in S} NC_{sfi} \cdot \phi_{ilst} - \sum_{i \in I} \sum_{f \in F} a_{if} x_{ilst} \geq om_{fi} - \beta_{hi} \cdot M \quad f \in F, l \in L_f, t \in T \quad (11)
$$

$$
\delta_{ilst} \geq \phi_{ilst} - (t \leq \phi_{ilst} - 1, 0) \quad s \in S, f \in F, l \in L_f, t \in T \quad (12)
$$

$$
\zeta_{hi} = of_i \cdot \sum_{i \in S} \sum_{i \in S} a_{if} \cdot y_{ilst} \quad f \in F, l \in L_f, t \in T \quad (14)
$$

$$
\sum_{i \in S} \sum_{i \in S} NC_{sfi} \cdot \phi_{ilst} - \sum_{i \in I} \sum_{f \in F} a_{if} x_{ilst} \geq om_{fi} - \beta_{hi} \cdot M \quad f \in F, l \in L_f, t \in T \quad (15)
$$

$$
\sum_{i \in S} \sum_{i \in S} NC_{sfi} \cdot \phi_{ilst} - \sum_{i \in I} \sum_{f \in F} a_{if} x_{ilst} \geq om_{fi} - \beta_{hi} \cdot M \quad f \in F, l \in L_f, t \in T \quad (16)
$$

The objective function given by (1) consists of outsourcing costs, overtime costs, shift pattern and shift change costs, inventory holding costs, and surcharges regarding to the overtime.

Constraints from (2) to (4) indicate capacity limitations on normal working time, overtime, and outsourcing. Inventory balance constraints are given by (5) and (6). Constraints (7) and (8) demonstrate safety stock levels and storage capacities of warehouses. Constraints (9) and (10) ensures that productions are on active shift patterns and constraints in (11) guarantee that only one shift pattern is selected in each period.
Constraints (12) ensure that the same shift pattern for normal working time and overtime is selected. The shift change logic is given by (13). The surcharge of overtime $o_f$ is calculated by (14). Constraints (15) to (17) guarantee that the reduction of the working time account at each production line within plant $f$ is smaller than $om_f$ and the total unused capacity of that production line. Constraints in (19) calculate the working time account at the end of each period by adding the surcharge of overtime of period to the balance of working time account during that period and extracting the taken vacation time $v_t$ from the working time account during that period. Constraints (20) and (21) guarantee that supplemental wages are paid if the balance of the working time account exceeds the upper limit. Finally, non-negativity constraints and binary variables are defined by (22) and (23).

5. Practical example

The selected company is a manufacturer of electronic components with two plants. Figure 1 shows the aggregated production lines 1, 2, and 3. Production line 1 within Plant I consists of work stations WS 1 and WS 2, production lines 2 and 1 within Plant II consist of WS 1, WS 2 and WS 1, WS 3 respectively. Plant I is fully automated and located in a high-wage country. Plant II is partially automated and is run with relatively cheaper labor costs in comparison to Plant I. 2 products are produced. Product A which has relatively high demand can be produced in all production whereas product B can only be produced in production line 3.

![Figure 1: Production lines and product assignments](image1)

The planning horizon is 12 months. Each month is considered as one discrete period. Demands for product A and B are deterministic and shown in Figures 2 and 3. Furthermore, we consider a minimum stock level (safety stock) for each product. Additionally, we consider one central warehouse with limited storage capacity for both plants. Transportation costs are not considered.

In our example, we set outsourcing costs relatively high. Therefore, outsourcing is selected only when the production capacity and inventory level cannot fulfill the demand.

Both plants can run on two different shift patterns. By the first shift pattern, called 3-shift pattern, plants are run with 15 shifts a week and 3 optional shifts on Saturdays as overtime. Under the second shift pattern, called 2-shift pattern, plants are run with 10 shifts a week and 2 optional shifts on Saturdays as overtime. Furthermore, the shift-dependent production costs, fix costs of overtimes and surcharges for overtime are determined for each shift pattern. For the working-time account, an upper limit of 80 hours is given. The account can be reduced at most by 20 hours per month. An account balance above 80 hours is paid as supplemental wage at the end of each period.

6. Numerical results

Figures 2 and 3 illustrate the production volumes and inventory levels over the planning horizon. We observe that the production volumes of product A vary quite closely around the demand and consequently the inventory level is kept at safety stock. The proposed production plan for product B builds up high inventory, since the inventory cost of product B is smaller than for product A.

![Figure 2: Trend of quantity of production, inventory, and demand for product A](image2)

![Figure 3: Trend of quantity of production, inventory, and demand for product B](image3)

The model suggests building up inventory for product B to fulfill its future demand and to release production capacity for product A.

Figures 4 to 6 demonstrate the capacity (abbreviated with “capa”) utilisation and the proposed shift patterns in the production lines (PL) over the planning horizon. From Figure 4, we observe that in production line 1 the shift pattern in the first 3 periods is the 3-shift pattern but then changes to the 2-shift pattern. Figures 5 and 6 indicate that the production lines 2 and 3 run only on a 3-shift pattern because the cost of running Plant I is...
relatively higher than Plant II as well as the 3-shift pattern causes more costs than the 2-shift pattern. Furthermore, since the inventory level at the beginning of the first period is not high, in order to fulfill the demand in the first periods, it is required that all plants run with their maximum capacity. But later, by building inventory for product B, more production capacity is released in order to fulfill the demand of product A and at the same time to keep Plant I running on a cheaper shift pattern.

Figure 4: Capacity utilisation and shift patterns in PL $l_1$

Figure 5: Capacity utilisation and shift patterns in PL $l_2$

Figure 6: Capacity utilisation and shift patterns in PL $l_3$

Table 1 indicates the behavior of the working time account. According to the supplemental times ($\xi_l$) shown in the first row, we observe that the total required overtime in Plant I is less than in Plant II. This is reasonable since the cost of doing overtime in Plant I is higher than in Plant II.

Table 1: Working time account of PL $l_1$, $l_2$, $l_3$ (in hours)

<table>
<thead>
<tr>
<th></th>
<th>$l_1$</th>
<th>$l_2$</th>
<th>$l_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\xi_l$</td>
<td>660</td>
<td>810</td>
<td>810</td>
</tr>
<tr>
<td>$\theta_l$</td>
<td>120</td>
<td>40</td>
<td>120</td>
</tr>
<tr>
<td>$\xi_s$</td>
<td>460</td>
<td>690</td>
<td>610</td>
</tr>
<tr>
<td>$\alpha_l$</td>
<td>80</td>
<td>80</td>
<td>80</td>
</tr>
</tbody>
</table>

The second row in Table 1 demonstrates the total vacation time which has been taken from the working time account, row 3 shows the total surcharge which has been paid, and finally, the last row shows the current status of the working time account in each production line which is reasonably at the maximum level.

Acknowledgements

The Project „KoKa | Development of a decision support system for capacity adjustments at optimal costs“ is supported by the „Österreichische Forschungsförderungsgesellschaft mbH“.

References