AN APPROACH FOR THE INTEGRATION OF PRODUCTION SCHEDULING AND INTER-FACILITY TRANSPORTATION WITHIN GLOBAL SUPPLY CHAINS

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ABSTRACT

On the operational level, production scheduling and transportation planning are usually carried out by different stakeholders, making locally bounded decisions. The integration of both tasks allows for a better management of disruptions that affect the effectiveness of the production and transportation systems. In this paper we study the integrated production and transportation scheduling problem (PTSP) for supply chains comprising an original equipment manufacturer as well as upstream suppliers. Based on a generic framework, the supply chain is structured into a chain of operational planning entities, where for each entity a PTSP arises. The scheduling is performed based on a mathematical programming formulation that takes the current capabilities of the production and transportation systems as well as the previous schedule into account. The computational results obtained are starting point for the development of heuristics.

Keywords: Production Scheduling, Transportation Planning, Global Supply Chains, Integrated Logistics

Track: Global Operations and Strategic Supply Chain Management or Supply Chain Management

1. INTRODUCTION

An unbalanced and unstable integration of manufacturing and transportation systems may weaken the competiveness of supply chains. This integration is even more relevant along global supply chains due to longer transportation lead-times and potential perturbations in manufacturing processes. Nowadays, production and transportation scheduling are carried out sequentially due to their complexity and current lack of appropriate heuristics for supporting a desirable integration on the operational level. Especially within dynamic environments, production and transportation systems must be properly integrated so that efficiency, responsiveness and flexibility could be achieved and sustained. Indeed, local decisions cannot only depend on the efficiency of the individual processes at different locations, but rather take into account the behaviour of linked decision systems.

In this paper we study the integrated production and transportation scheduling problem (PTSP) for supply chains comprising one original equipment manufacturer as well as upstream suppliers. Based on a generic framework, the supply chain is structured into a chain of operational planning entities, where for each entity a PTSP arises. The scheduling is performed based on a mathematical programming formulation that takes the current capabilities of the production and transportation systems as well as the previous schedule into account. The computational results obtained are starting point for the development of heuristics.

The present paper is structured as follows. Section 2 reviews relevant literature. In Section 3 our generic approach for the integrated production and transportation scheduling problem (PTSP) along global supply chains is presented. The mathematical program for the integrated production and transportation scheduling is formulated in Section 4. The computational analysis is based on a test case in Germany and presented in Section 5. The paper closes with some discussion and implications in Section 6.

2. LITERATURE REVIEW

Sequential and hierarchical schemes for production scheduling and transportation planning have been deployed with consistent performance for stable surroundings. When dealing with dynamic environments, integrative concepts and tools are necessary. Recent approaches for the integration of production and transportation systems do not consider current capabilities, level of utilisation of resources and transit-/lead-times. This limitation has special relevance in supply chains, where components of production and logistics must be properly integrated so that efficiency, responsiveness and flexibility could be achieved and sustained.

2.1. Production and Transportation Scheduling Problem

Resources and their employment level have to be better considered in production and transportation systems so that decision making in the dynamic and competitive environment of supply chains is enhanced. These systems are nowadays managed by advanced planning systems (APS's). The current underlying structure of APS's can be illustrated by the Supply Chain Planning Matrix (Figure 1).

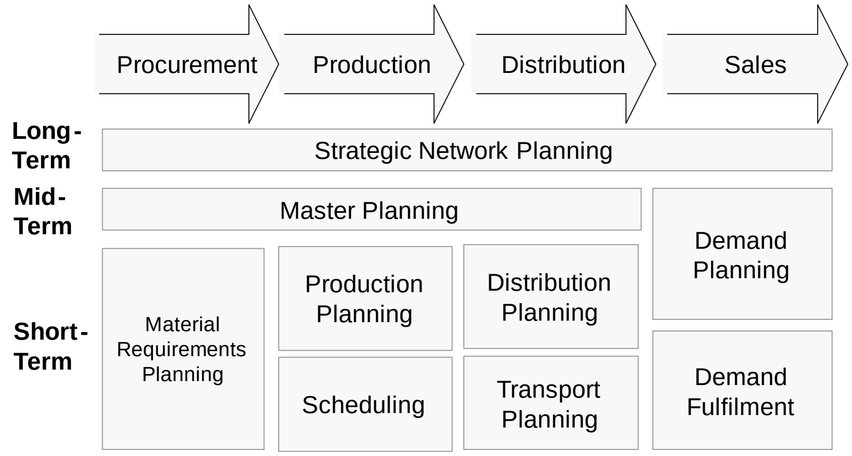

Figure 1 – Supply chain planning matrix (Rohde et al., 2000)

The matrix comprises modules for the planning tasks that are characterised by time horizon and involved business functions. The degree of detail increases and the planning horizon decreases by shifting from the long-term to the short-term. In order to align the processes at different locations and business functions, planning tasks on the strategic (strategic network planning) and tactical level (master planning) are usually carried out by a central planning entity. Due to the large amount of data that needs to be considered and the large number of decisions, the operational planning is normally carried out independently in a sequential way by each location and business function (Fleischmann et al., 2004). These individual planning tasks are performed by model-based decision systems that often include the utilisation of mathematical models or heuristics for determining optimal plans/solutions. So far, these models do not take dynamic environments or perturbations appropriately into account (Scholl, 2001). For instance, a breakdown of a machine or a transportation vehicle can be considered as internal perturbations. Traffic jams are examples of external perturbations that extend the travel time between locations.

The problem of coordinating supply chain stages can be handled by a monolithic (central) approach, where the schedules are determined simultaneously, or a hierarchical and sequential approach (Sawik, 2009). The central approach is usually not practicable in real-world situations due to unfeasible requirements in terms of information availability and communication capabilities.

Currently, on the operational level, production scheduling is handled sequentially by means of heuristic approaches. Wang and Cheng (2009a) developed an approach for the identical parallel-machine scheduling problem and analysed their performance bounds. Ant colony optimisation (ACO) – a meta-heuristic – was deployed by Lin et al. (2008). They applied an ACO algorithm to two NP-hard flow-shop scheduling problems, solving them to a certain scale by producing schedules of better quality. Furthermore, Huang and Yang (2008) deployed the ACO approach to overlapping production scheduling planning with multiple objectives: machine idle time, job waiting time, and tardiness. Finally, Valente and Alves (2007) compared the performance of a varied set of heuristics, including simple scheduling rules, early/tardy dispatching heuristics, a greedy procedure and a decision theory heuristic.

Transportation scheduling and vehicle routing has also been addressed with the deployment of heuristics. Park (2001) applied a hybrid genetic algorithm for the vehicle scheduling problem with service due times and time deadlines aiming on the minimisation of total vehicle travel time, total weighted tardiness, and fleet size. Raa and Aghezzaf (2008) approached the challenge of minimising overall costs in an integrated distribution and inventory control system. For that, they proposed a heuristic that is capable of solving a cyclical distribution problem involving real-life features. Herer and

Levy (1997) dealt with the metered inventory routing problem. They solved it on rolling time horizon, taking into consideration holding, transportation, fixed ordering, and stock out costs. Cheung et al. (2008) developed a mathematical model for dynamic fleet management. The solution proposed addresses first the static problem and then provides an efficient re-optimisation procedure for updating the route plan as dynamic information arrives. Hwang (2005) addressed an integrated distribution routing problem for multi-supply centers using a genetic algorithm in three steps: clustering, vehicle routing with time constraints and improving the vehicle routing schedules.

Even though these sophisticated heuristic approaches achieved exceptional results in handling isolated scheduling tasks – either production or transportation – they are not able to materialise the competitiveness obtained by a combined view of production and transportation systems. By utilising the combined flexibility of both systems, challenges triggered by a dynamic changing environment (e.g. perturbations) can be better handled. Therefore, an integrated alignment of production and transportation scheduling at the operational level holds a great potential for strengthening the competitiveness of supply chains.

The integrated production and transportation scheduling problem (PTSP) with capacity constraints is well known in the literature. An optimal solution for the PTSP requires solving the production scheduling and transportation routing simultaneously. PTSP is normally motivated by perishables products so that production and transportation of these short-lifespan products are synchronised. Furthermore, the classic PTSP focuses on constraints connected rather to production capacities than to transportation times and costs (Hochbaum and Hong, 1996; Tuy et al., 1996; Sarmiento and Nagi, 1999).

These approaches often assume the transportation to be instantaneous and do not address the routing of the transportation vehicles. The nature of PTSP’s leads to a mathematical program that is NP-hard in the strong sense. Even for small scenarios an excessive computational power is needed. Thus the challenge is to set up heuristics that can timely lead to near optimal solutions/schedules.

Several insights and concepts for the integration of production and transportation have been developed in the recent years (e.g. Cohen and Lee, 1988; Chandra and Fisher, 1994; Haham and Yano, 1995; Thomas and Griffini, 1996; Fumero and Vercellis, 1999; Funda Sahin et al., 2008). But most of these concepts focus either on the strategic or tactical level (Chen, 2004). Papers that deal with detailed schedules for the transportation can be classified according to the objectives of applied mathematical programs and heuristics. One group only considers the lead time for production and transportation of orders (e.g. Potts, 1980; Woeginger, 1994 and 1998; Lee and Chen, 2001; Hall et al., 2001; Geismar et al., 2008). The second group takes lead times and associated costs into account (e.g. Hermann and Lee, 1993; Chen, 1996; Cheng et al., 1996; Wang and Cheng, 2000; Hall and Potts, 2003; De Matta and Miller, 2004; Chen and Vairaktarakis, 2005; Pundoor and Chen, 2005; Chen and Pundoor, 2006; Stecke and Zhao, 2007). Although the determination of detailed schedules for the production and transportation represents a good achievement, the routing of the utilised transportation vehicles has to be properly considered. This challenge is only addressed by a few authors (e.g. Li et al., 2005; Geismar et al., 2008).

The trade-offs between costs and service level in the interface of production and distribution processes has been investigated in recent years. One approach is the transport-oriented production scheduling. It stands for the provision of tactical and operational information from logistic services providers to manufactures in order to reduce lead-times and costs along specific distribution chains (Scholz-Reiter et al., 2008). The problem of balancing the production and delivery scheduling so that there is no backlog and production, inventory and distribution costs are minimise is addressed by Pundoor and Chen (2009). Li et al. (2008) studied a coordinated scheduling problem of parallel machine assembly and multi-destination transportation in a make-to-order supply chain. Their approach decomposes the overall problem into a parallel machine scheduling sub-problem and a 3PL (third-party logistic provider) transportation sub-problem. By means of computational and mathematical analysis, the 3PL transportation problem is shown to be NP-complete, therefore heuristic algorithms are proposed to solve the parallel machine assembly scheduling problem.

In general the above literature is dedicated to be applicable for special settings and therefore no generic approach for the integration of production scheduling and transportation planning along supply chains exists. This means that they are not suitable for a generic and fully integrated structure of a supply chain; do not consider perturbations or a rolling time horizon. Furthermore, most of them do not analyse routing decisions, which have to be part of an advanced PTSP approach.

2.2. Integration and Performance of Supply Chains

Local decisions cannot only depend on the efficiency of the individual processes at different locations, but rather take into account the behaviour of linked decision systems. The idea of managing the integrated supply chain and transforming it into a highly agile and adaptive network certainly provides an appealing vision for managers (Surana et al., 2005). Successful supply chain integration depends on the ability of partners to collaborate so that information is shared. In particular, production and transportation systems must exchange information so that plans and schedules are aligned. Scheduling tasks become more complicated because legally independent companies are constantly interacting in situations of information asymmetry. Information asymmetry arises due to fact that each legally independent partner usually owns a set of private information (e.g. costs, level of utilisation) that the partner is, in general, not willing to share (Dudek, 2004). Fostering trust and collaboration – requirements to higher performance in the supply chain – in this kind of situation is challenging (Panayides and Venus Lun, 2009).

One early attempt of vertical coordination by collaborative planning is the Joint Economic-Lot-Size-Model from Banerjee (1986). This approach shows on the one hand that only an aligned ordering and production policy of buyer and manufacturer is able to make full use of their commercial partnership. On the other hand the approach also states that the outcome of a collaborative planning process is strongly dependent on the available information and distribution of power between the partners. These results are also valid for supply chains.

In the literature only a few collaborative planning schemes have been developed for the purpose of aligning operational activities of partners. Up to now, the majority of these schemes is based on a multi-level capacitated lot sizing problem and does not consider a rolling time horizon (Stadler, 2009). A collaborative planning scheme, which takes into account the decision situation of the involved partners in downstream direction of the material flow, is upstream coordination (Bhatnagar et al., 1993). One possibility to improve the results of upstream coordination is to merge the planning activities of several partners into one planning entity. These entities comprise several partners that are coordinated by central planning. The planning entities themselves are further on coordinated by upstream planning. Pibernik and Sucky (2007) show that by reducing the number of individual planning partners and increasing the number of planning entities the competitiveness of the whole supply chain can be increased.

The potential for further improvements of collaborative planning schemes is caused by not only considering the decision situation of the partners in downstream direction but rather the objectives and constraints of partners in the upstream direction of the material flow. For instance, the hierarchical coordination mechanism presented by Zimmer (2001) tries to overcome this deficit. An approach to weaken the hierarchical relationship between the partners is the introduction of negotiation-based coordination instead of pure upstream coordination. The bilateral negotiation based collaborative planning scheme proposed by Dudek (2004) uses upstream planning at the initialisation and afterwards a negotiation process in order to improve the overall performance. The exchange of cost information represents the major drawback of this low-hierarchical approach. Giannoccaro and Pontrandolfo (2009) argues that revenue sharing (RS) could be deployed as coordination mechanism for aligning the incentives of independent supply chain actors so as to induce them to act in such a way that is optimal for the supply chain as a whole.

The establishment of collaborative relationships among supply-chain partners is a requisite for iteratively aligning independent entities in supply chains. Nevertheless, approaches for structuring this collaboration still lack the ability to be implemented. Specifically in regard to production and transportation systems, a comprehensive scheme for handling this integration on the operational level does not exist. Building scheduling approaches that integrate supply, production and distribution and could also deal with various machine processing environments embodies an important research challenge (Wang and Cheng, 2009b).

3. INTEGRATED APPROACH FOR PTSP'S IN SUPPLY CHAINS

Centralised solutions for the production scheduling and transportation planning processes along supply chains are not practically applicable due to overwhelming eyesight and communication requirements. On the operational level, these processes are currently carried out sequentially due to their complexity and current lack of appropriate heuristics for supporting a desirable integration. Considering that the performance of a supply chain could be significantly improved – in terms of both service level and costs – by applying an integrated instead of sequential scheduling schemes on the operational level (Chen e Vairaktarrakis, 2005), a generic approach for the integration of production scheduling and transportation planning in supply chains is proposed. This generic approach embraces a chain of operational planning entities that perform the PTSP as well as a mechanism for supporting the alignment between these entities.

Supply chains are composed by a chain of production stages, starting at the suppliers of raw material, followed by several production facilities and ending at the OEM. These production stages as well as the final customers are linked by transportation systems.

The proposed operational planning entities comprise the production scheduling and transportation planning of one facility along the supply chain (Figure 2).

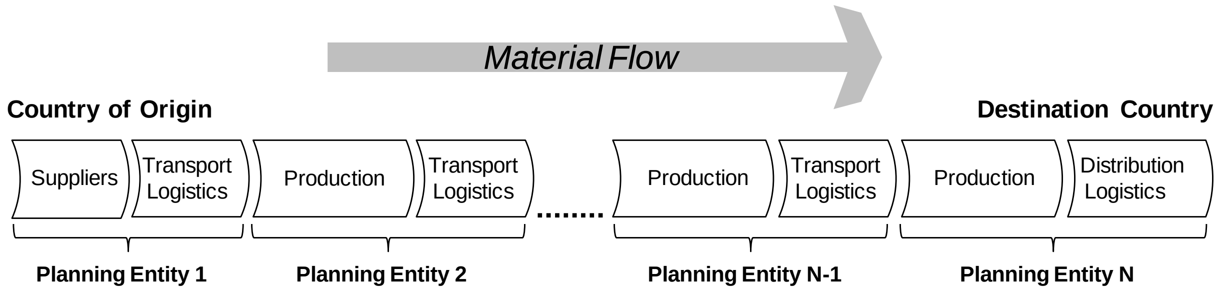

Figure 2 – Chain of planning entities on the operational level (Scholz-Reiter et al., 2009)

Therefore, one entity carries out the scheduling for one production facility and associated transportation to either the next production facility or final customers. The scheduling tasks of the entities (Figure 3) are aligned by order delivery dates. These dates specify when an order has to be delivered to the subsequent production facility or the final customer. The scheduling of the orders is based on the order delivery dates $d_{j,n}$, which are provided by upstream planning. In this context, the starting point is the desired delivery date to the customer.

Since each entity performs the PTSP, they can materialise the competitive advantage provided by combining the flexibility of production and transportation systems. Each entity has not only to set up a production and transportation schedule that is suitable for its own specifications of delivery dates but also for the specifications of directly connected entities. In order to ensure the delivery of orders the entities have the flexibility to contract external production processing or transportation capacity.

Each entity strives to achieve a certain service level in regard to the in-time delivery of orders and to minimise the costs for production and transportation.

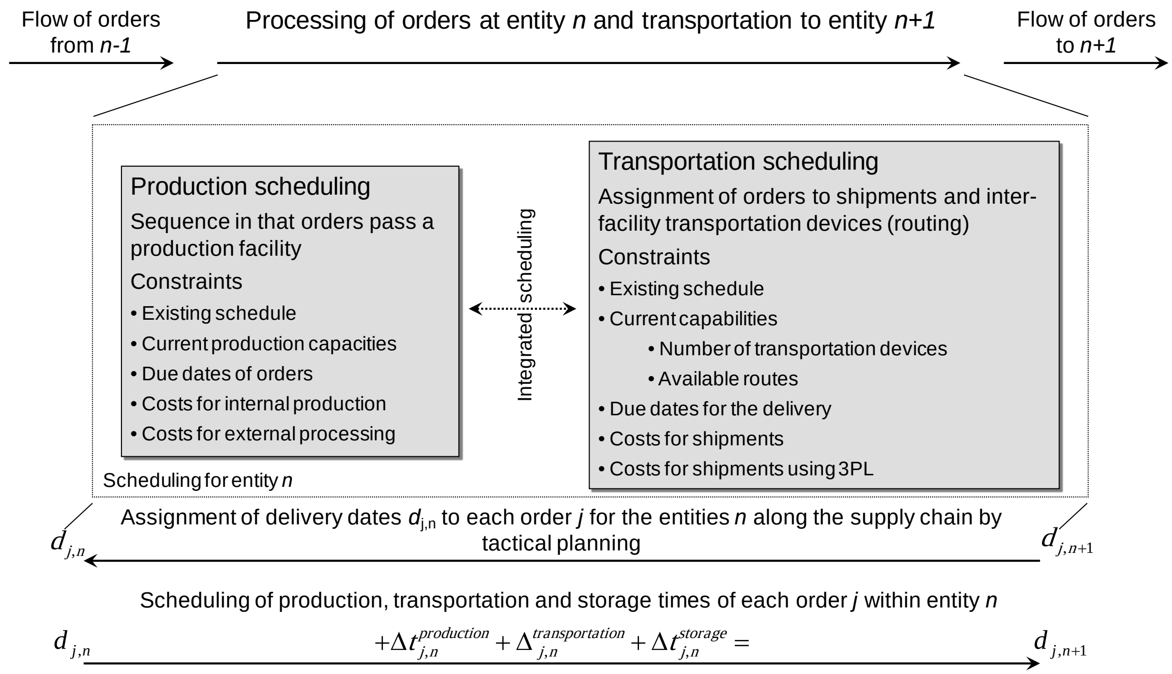

Figure 3 – Scheduling within the planning entities

Therefore a schedule for all orders is set up and the dates for production, transportation and, if necessary, storage are derived. This schedule is subject to the constraints given by the existing schedule, current capabilities of the production and transportation system, delivery dates of the orders and associated costs for internal production or external processing.

A scheduling scheme at the operational level needs to be run in successive way. This is motivated by the arrival of new orders, perturbations as well as variations of current capabilities within the production and transportation systems. Indeed, the current iteration has to consider the existing schedule from the previous iteration as well as new orders. In the intervening time between these iterations, capabilities and employment level of involved production and transportation system may change due to either planned events like maintenance of a machine or a transportation device as well as perturbations like the breakdown of a machine or the flooding of a road. Therefore, the iteration time should be reduced in order to maximise the adaptability of the supply chain to dynamics. With the acceleration of these feedback loops an on-line optimisation mechanism for supply chain priorities will emerge.

The generic approach provides a concept for the integration of production and transportation systems, which considers the capabilities, level of utilisation of resources and transit-/lead-time of both systems on the operational level. The approach supports the handling of perturbations and oscillations on a rolling time horizon. So far no proposed scheduling scheme in the literature takes the rolling time horizon of the performed operations into account. The design of integrated processes on the operational level of supply chains is a pressing challenge for both practitioners and scientists. The concept answers to the demand of new approaches that deliver effective integration and competitiveness gains to the supply chains. The generic approach embodies an overall concept applicable to different industries. On the sequence, a mathematical program formulation tailored for the entities that manage production and inter-facility transportation is formulated and tested in Section 5.

4. MATHEMATICAL MODELLING OF THE INTEGRATED PTSP

Different departments within supply-chain partners usually perform the production scheduling and the transportation planning making locally-bounded decisions. As a drawback, the obtained results may be locally optimal but do not pay attention to the requirements of connected systems or the whole supply chain. In this section a mathematical programming formulation of the PTSP that address the pressing challenge of integrating production and transportation systems is introduced. The mixed-integer program (MIP) for the operational level combines the production scheduling of a planning entity and the associated transportation of orders to the subsequent facility is introduced in the following. The program considers delivery dates of the orders, current capabilities of production and transportation systems as well as the requirements of a rolling time horizon.

4.1. Model Assumptions

The applied production scheduling is based on a heterogeneous open flow-shop with several consecutive production levels. Each production level consists of several machines, which feature an order-type specific processing time and processing cost. All orders have to be processed at one machine at each production level. Furthermore, orders can be processed externally in a very short time but causing a comparatively high cost.

The orders are assigned to tours for the transportation to the subsequent production facility. If at least one order is assigned to a tour this tour is conducted. In this case fixed and variable costs occur. The variable costs depend on the duration of the tour. The duration of each tour is pre-given. This means that the program does not take the routing decisions. Since the shortest path through the transportation network is for each tour the same in the case of inter-facility transportation, the required duration is calculated in advance and given as an input to the program. For this purpose an open vehicle routing formulation is employed. All considered tours start at production facility and end at the subsequent production facility and do not return. A new tour can be conducted as soon as a transportation device becomes available. This is for instance the case when a tour from a preceding production facility arrives. Each tour has a limited transportation capacity that cannot be exceeded. The delivery of orders cannot be late. An early delivery to the subsequent facility is penalised. In addition, orders can be shipped directly to a customer in-time by a 3PL. This shipping alternative will induce a high extra cost.

The program can cope with a rolling time horizon by initialising orders that are already in production or that are ready for shipping. Perturbations affecting production or transportation resources can be considered by adjusting the related parameters between two consecutive planning runs. External processing and the usage of a 3PL ensure the feasibility of the program. In the case that an order is assigned to external processing or transportation by the 3PL, only extra costs are applied and no additional decisions have to be taken.

4.2. Nomenclature

Sets

J	Customer orders
T	Order types
$T^{j}_{j,t}$	Assignment of j and t
N	Production levels
$N^{p}_{j,n}$	Production levels of order j
M	Machines
M^{e}_{n}	Machines at production level n

V Tours to customers

$A^{tour}_{j,v}$ Assignment of orders j to tours v

$A^{seq}_{j,j'}$ Assignment of order sequence j, j'

$A^{mach}_{j,n,m}$ Assignment j to m on n

Parameters

c^{ep}_{j} Costs for external processing of j

c^{d} Costs for delayed delivery

c^{dv} Variable costs of tour v

c^{fv} Fixed costs of tour v

$c^{p}_{j,t,n,m}$ Processing costs of j at n on m

c^{3pl} Costs for 3PL

d Travel time of v between the production location to the subsequent facility

M BigM; large scalar

$pt_{j,t,n,m}$ Processing time of j at n on m

r_j Required transportation capacity

$\bar{r}_v$ Transportation capacity of v

$t^{a}_{j,n}$ Supply date of order j

t^{av}_{v} Earliest departure date of tour v

t^{dd}_{j} Desired delivery date of j

Positive Variables

$T^{c}_{j,n}$ Completion time of j at m on n

T_j^d Delivery delay of j to the subsequent facility

T_v^s Start time of tour v

Binary variables

$X_{j,n,m}$ j is processed at m on n

$Y_{j,j',n}$ j is processed before j' on n

$A_{j,v}$ j is assigned to tour v

O_v Tour v is conducted.

E_j External processing of order j

L_j Order j is transported by a 3PL

4.3. Mathematical Model

The production of an order is assigned in equation (1) to one machine at each production level that needs to be passed by this order. Since the model is designed for a rolling time horizon, the number of production levels decreases for a specific order between consecutive planning runs. Furthermore, the production can be carried out by an external provider. In this case no machine is assigned at all levels that need to be passed.

$$\sum_{m \in M_n^e} X_{j,n,m} = \left(1 - E_j\right) \qquad \left(j \in J; n \in N_{j,n}^p\right) \qquad (1)$$

The completion time of an order at a given production level has to be greater than the sum of the completion time at the previous production level and the required processing time of the assigned machine. In the case that a planning is carried out while an order is processed on a machine the required production time is adapted to a remaining processing time. Furthermore the assignment of job, production level and machine is fixed under such circumstances.

$$T^{c}_{j,n-1} + t^{a}_{j,n} + \sum_{m \in M^{e}_{n}} pt_{j,t,n,m} X_{j,n,m} \leq T^{c}_{j,n} \qquad \left(j \in J; t \in T : j,t \in T^{j}_{j,t}; n \in N^{p}_{j,n}\right) \qquad (2)$$

$$X_{j,n,m} = 1 \qquad \left(j \in J; n \in N^{p}_{j,n}; m \in M^{e}_{n} \wedge A^{mach}_{j,n,m}\right) \qquad (3)$$

The processing of orders is scheduled by equations (4) to (6). Equation (4) and (5) ensure that at each point in time only one order is processed at a certain machine. The results of a previous scheduling can be considered partly by enforcing the obtained sequence of orders at the production levels by equation (6).

$$1 - \left(2 - X_{j,n,m} - X_{j',n,m}\right) M \leq Y_{j,j',n,m} + Y_{j',j,n,m} \leq X_{j,n,m} \qquad (4.1)$$

$$\left(j, j' \in J : j \neq j'; n \in N^{p}_{j,n} \wedge N^{p}_{j',n}; m \in M^{e}_{n}\right)$$

$$1 - \left(2 - X_{j,n,m} - X_{j',n,m}\right) M \leq Y_{j,j',n,m} + Y_{j',j,n,m} \leq X_{j',n,m} \qquad (4.2)$$

$$\left(j, j' \in J : j \neq j'; n \in N^{p}_{j,n} \wedge N^{p}_{j',n}; m \in M^{e}_{n}\right)$$

$$\begin{aligned} T^{c}_{j,n} + pt_{j',t,n,m} \quad \leq \quad & T^{c}_{j',n} \\ & + M(2 - X_{j,n,m} - X_{j',n,m}) \\ & + M\left(1 - Y_{j,j',n,m}\right) \end{aligned} \qquad (5)$$

$$\left(j, j' \in J : j \neq j'; t \in T : j,t \in T^{j}_{j,t}; n \in N^{p}_{j,n} \wedge N^{p}_{j',n}; m \in M^{e}_{n}\right)$$

$$Y_{j,j',n,m} = 1 \qquad \left(j, j' \in J : j, j' \in A^{seq}_{j,j'}; n \in N^{p}_{j,n} \wedge N^{p}_{j',n}; m \in M^{e}_{n}\right) \qquad (6)$$

In the case that an order has been already passed the production at the execution time of the planning, the completion time at the last production level is assumed to be zero. Hence, it is immediately available for transportation. Note that the completion time of an externally processed order is assumed to be larger than its arrival time for processing. Furthermore we assume that each order has been processed before the desired delivery date. This is guarantees a timely production in the case that a 3PL is used for the transportation.

$$T^{c}_{j,n} \leq 0 \qquad \left(j \in J; n \in N : N^{p}_{j,n} = \varnothing\right) \qquad (7.1)$$

$$T^{c}_{j,N} \geq t^{a}_{j,n} - M(1-E_{j}) \qquad \left(j \in J; n \in N\right) \qquad (7.2)$$

$$T^{c}_{j,N} \leq t^{dd}_{j} \qquad \left(j \in J\right) \qquad (7.3)$$

Each order is assigned to one tour; partial deliveries are not allowed. In addition it is possible to use a 3PL for the transportation of orders. Hence, the delivery of the order to the subsequent production facility is accomplished in-time by an external provider. The results of the previous planning are taken into account by fixing the assignment of orders and tours.

$$\sum_{v \in V} A_{j,v} = \left(1-L_{j}\right) \qquad \left(j \in J\right) \qquad (8)$$

$$A_{j,v} = 1 \qquad \left(j \in J; v \in V : j,v \in A^{tour}_{j,v}\right) \qquad (9)$$

A regular tour from the considered production facility to the subsequent facility can start as soon as all assigned orders are manufactured and the transportation device is available. Furthermore, the departure time for a not conducted tour equals zero.

$$T^{s}_{v} \geq T^{c}_{j,n} - M\left(1-A_{j,v}\right) \qquad \left(j \in J; n = N; v \in V\right) \qquad (10)$$

$$T^{s}_{v} \geq t^{av}_{v} - M\left(1-A_{j,v}\right) \qquad \left(j \in J; v \in V\right) \qquad (11)$$

$$T^{s}_{v} \leq O_{v} M \qquad \left(v \in V\right) \qquad (12)$$

In the case that at least one order is assigned to a tour the tour is conducted.

$$\sum_{j \in J} A_{j,v} \leq O_{v} M \qquad \left(v \in V\right) \qquad (13)$$

Each tour has a limited transportation capacity that cannot be exceeded.

$$\sum_{j} A_{j,v} r_j \leq \bar{r}_v \qquad (v \in V) \qquad (14)$$

The delivery of orders cannot be late in order to ensure the availability of orders for the processing at the subsequent production facility. Here the previously calculated travelling time within the transportation network is considered instead of a comprehensive routing problem.

$$T_v^s \leq t_{i,j}^{dd} - d + M\left(2 - A_{j,v} - O_v\right) \qquad (i \in I; j \in J; v \in V) \qquad (15)$$

$$T_j^d \geq t_{i,j}^{dd} - T_v^s - d - M\left(2 - A_{j,v} - O_v\right) \qquad (i \in I; j \in J; v \in V) \qquad (16)$$

The objective function minimises the costs for processing of orders, early deliveries and as well the fixed and variable costs of each conducted tour. Furthermore, it takes the costs for external processing of orders and the delivery to customers by using 3PL into account.

$$\begin{aligned} Min. \quad & \sum_{j \in J} \sum_{\substack{t \in T: \\ j,t \in T_{j,t}^j}} \sum_{n \in N} \sum_{m \in M_n^e} X_{j,t,n,m} c_{j,t,n,m}^p + \sum_{j \in J} T_j^d c_j^d \\ & + \sum_{v \in V} \left(O_v c^{fv} + c^{dv} d\right) \\ & + \sum_{j} \left(E_j c^{ep} + L_j c^{3PL}\right) \end{aligned} \qquad (17)$$

5. COMPUTATIONAL ANALYSIS

In this section the formulated mathematical program for one planning entity within a supply chain is applied to a test case in Germany. The test case consists of one production facility located in Kassel. The considered factory ships orders of intermediate products to the subsequent production facility in Dresden. A level production process, which was described by Scholz-Reiter et al. (2005), is carried out at the factory in Kassel. The structure of the material flow within the production facility and the structure of the transportation network are shown in Figure 4. The edges of the transportation network are weighted with the required travelling time between the locations of the network.

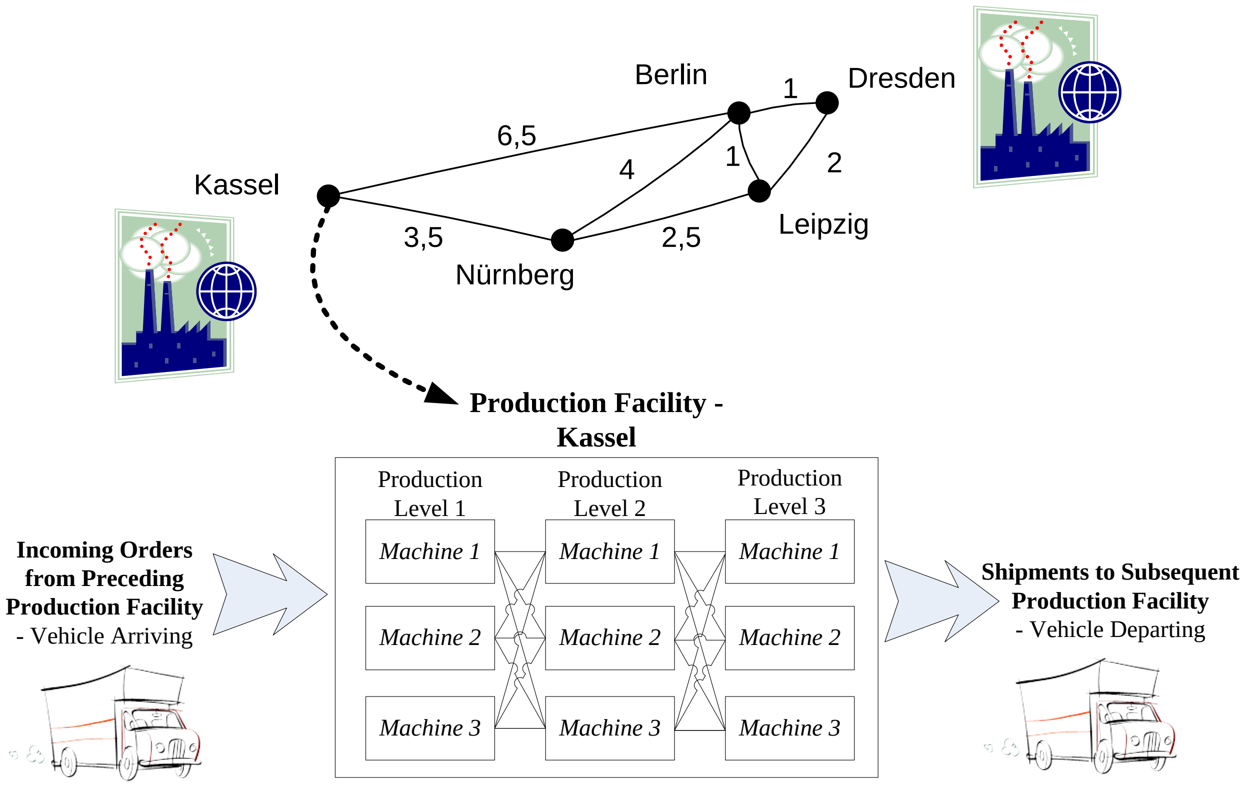

Figure 4 – Structure of the test case scenario

The proposed mathematical formulation of the integrated production and transportation scheduling problem has been implemented in GAMS 22.8. For simplicity all costs are in general chosen to be 1. The processing times of the three different order types for each machine are given by Scholz-Reiter et al. (2005). The processing costs are proportional to the required time of processing. In the case that a tour is conducted a fixed cost of 10 occurs. External processing of orders triggers costs of 12 and the usage of 3PL costs 10. The required transportation capacity is assumed to be 1 for all orders. Each transportation device has a maximal transportation capacity of 5 units. The considered test instances can comprise up to five transportation devices that arrive at the following points in time: 0, 5, 10, 15 and 20. At the same point in time up to five additional orders become available for processing. The due dates for the delivery of orders to the subsequent production facility depend on the date of provision of the orders at the planning entity and are given by the following points in time: 17, 22, 25, 32 and 35.

Since, the mathematical formulation is a MIP the instances could be solved by CPLEX 11. The computation was carried out on a 2.33GHz dual-core computer with 2GB of RAM in a deterministic mode of CPLEX with two threads.

Our computation analysis indicates two major findings. Costs can be significantly reduced and lead-times can be shortened by properly combining the flexibilities of production and transportation systems. For instance, if there is a peak on the utilisation of the production system, the available time for processing of orders, which can be delivered in short time, can be extended. Hence, external processing and extra costs can be avoided. In a situation where the transportation process requires more time than anticipated, the sequence of production can be rearranged so that currently urgent orders are early available for transportation. Furthermore, the mean values of due dates utilised in the upstream planning can be reduced by shortening required buffering times.

Since decisions on the operational level have to be taken within seconds or minutes one drawback related to this integrated approach of production and transportation systems is the required computational time. This is clearly displayed by the results for the test instances in Table 1.

Transportation devices	Orders	Computational time [sec]	Gap to optimal solution
1	3	0.281	0.00%
1	5	0.359	0.00%
2	7	0.438	0.0%
2	10	0.464	0.0%
3	13	0.578	0.0%
3	15	0.782	0.0%
4	17	0.752	0.0%
4	20	1.140	0.0%
5	23	1.860	0.0%
5	25	+600.0	1.21%

Table 1 – Computational time and gap to the optimal solution after 600 seconds

The table shows the required computational time and the relative gap between the best integer solution and the best node remaining after 600 seconds. For very small instances the optimal solution can be obtained within this time. Hence, the program can support a sustainable alignment of production and transportation systems by suggesting a schedule to the involved stakeholders. In the case of an increasing number of orders and transportation devices the need for a heuristic is demonstrated.

6. DISCUSSION AND IMPLICATIONS

Existing approaches for the integrated production and transportation scheduling problem (PTSP) with capacity constraints are often not applicable for the operational management of supply chains. In this paper we presented a generic approach for the PTSP that fosters a sustainable management of production and transportation systems along whole supply chains. To this end we introduced a chain of operational planning entities that perform the PTSP. The concept answers to the demand of new approaches that deliver effective integration and competitiveness gains to supply chains. The generic approach embodies an overall concept applicable to different industries.

One mathematical program formulation for the case of inter-facility transportation was formulated. This formulation can be applied on a rolling time horizon and takes dynamic changing capabilities of the transportation and production into account. The approach could support a sustainable alignment of production and transportation systems by suggesting a schedule to the involved stakeholders. In the case of increasing number of orders and transportation devices the need for a heuristic that is able to solve larger instances with good results in feasible time is demonstrated.

ACKNOWLEDGEMENTS

This research was supported by the German Research Foundation (DFG) as part of the Brazilian-German Collaborative Research Initiative on Manufacturing Technology (BRAGECRIM).

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