ASSESSING THE INTEGRATED SCHEDULING OF MANUFACTURING AND TRANSPORTATION SYSTEMS ALONG GLOBAL SUPPLY CHAINS

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ABSTRACT

Seeking for benefits related to country-specific advantages and the expertise of excellent partners supply chains often embrace globally distributed manufacturing systems. These locally obtained benefits might be impaired as a result of the unbalanced integration of manufacturing and transportation systems. Indeed, due to longer transportation lead-times and potential perturbations in manufacturing processes, this integration is even more important in global supply chains.
This paper presents a generic approach for the integration of production and transportation scheduling along global supply chains and compares its performance with a sequential approach. The generic approach is based on the integrated production and transportation scheduling problem (PTPS). The results of the computational analysis demonstrate that the proposed integrative approach outperforms the sequential one. Even though the outcome is based on mathematical programs with limited capabilities in regard to the number of scheduled orders, it provides solid motivation and support for the forthcoming development of heuristics for integrating manufacturing and transportation scheduling.

Keywords: Scheduling, Transportation, Manufacturing, Global Supply Chains

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.

This paper compares the performance of an integrated generic approach for the production and transportation scheduling and the sequential approach currently deployed in Advanced Planning Systems (APS). The generic approach is based on the integrated production and transportation scheduling problem (PTPS) and provides a concept for applying it on the operational level to a supply chain with several production locations. For that, the production scheduling and the vehicle routing of each location of the supply chain are grouped in scheduling entities. The 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.

The performance in terms of costs and punctuality of the following cases are compared: (i) each entity deploys the integrated mathematical program and (ii) each entity deploys two separated mathematical programs for the production scheduling and the transportation scheduling. The results of the computational analysis demonstrate that the proposed integrative approach for simultaneous scheduling of manufacturing and transportation systems outperforms the sequential one. The outcome is based on mathematical programs with limited capabilities in regard to the number of scheduled orders. Even though, it provides solid motivation and support for the forthcoming development of heuristics for integrating manufacturing and transportation scheduling.

The present paper is structured as follows. Section 2 reviews the relevant literature. In Section 3 the generic approach for the integrated production and transportation scheduling problem (PTSP) along global supply chains is presented. The mathematical formulations for the sequential and integrated production and transportation scheduling are presented on Section 4. Section 5 is dedicated to the presentation of the test scenario, based on which the sequential and integrated approaches are computationally tested and compared. Some discussion and implications are outlined 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).

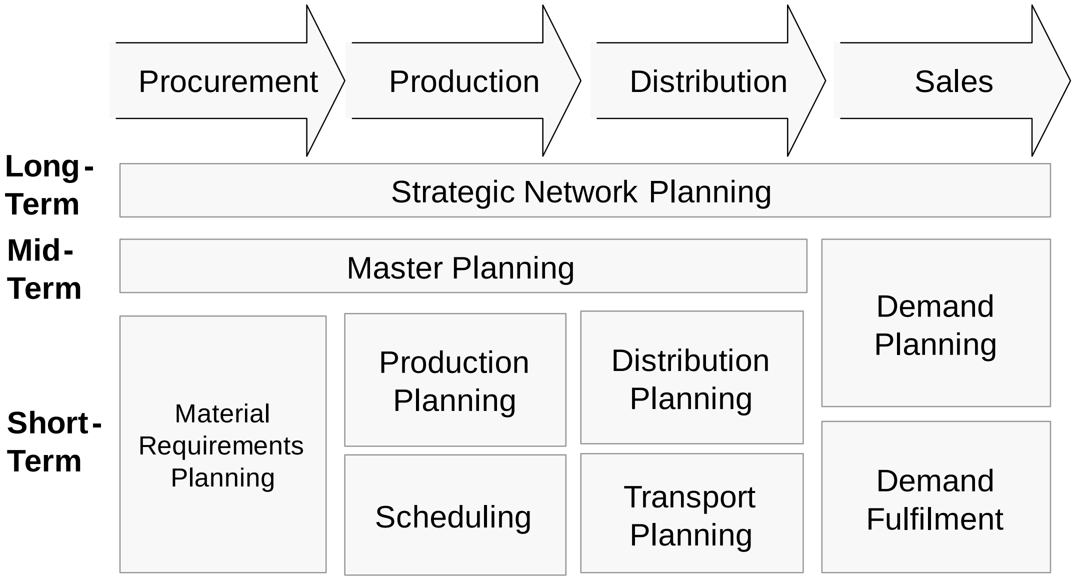

Figure 1 – Supply chain planning matrix (Rohde et al., 2000)

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 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

Informational integration and synchronisation across functional and organisational boundaries in supply chains are major challenges. Overcoming them depends on better understanding tangible (e.g. technological) and intangible (e.g. cultural) barriers as well as on developing proper integration concepts, approaches and tools. The influence of human, technological, and organisational aspects on the interfaces between processes that underpin the performance of supply chains has been substantiated (Marble and Lu, 2007; Panayides and Venus Lun, 2009). Indeed, the interfaces between production and transportation systems can be improved based on the mutual understanding of differences between connected functions, organisations and contexts (Frazzon, 2009).

The outcome of the scheduling process is influenced by the scheduler adding human capabilities that cannot be automated and by the scheduling software tools at hand (Berglund and Karltun, 2007). Indeed, the performance of supply chains is becoming more and more dependent on available technologies. Reasons for this are the increasing supply, production and distribution complexities in combination with higher incidence of potentially disruptive factors (Windt and Hülsmann, 2007). In order to cope with these requirements, the deployment of new concepts and technological tools is urgent (Trienekens and Beulens, 2001).

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 the 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). Mentioned gaps will be addressed in the following sections.

3. GENERIC APPROACH

The generic approach is based on the integrated production and transportation scheduling problem (PTPS) and provides a concept for applying it on the operational level to a supply chain with several production locations. For that, the production scheduling and the vehicle routing of each location of the supply chain are grouped in scheduling entities.

Centralised solutions for the production scheduling and transportation planning processes of a whole 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). Therefore, one entity carries out the scheduling for one production facility and associated transportation to either the next production facility or final customers.

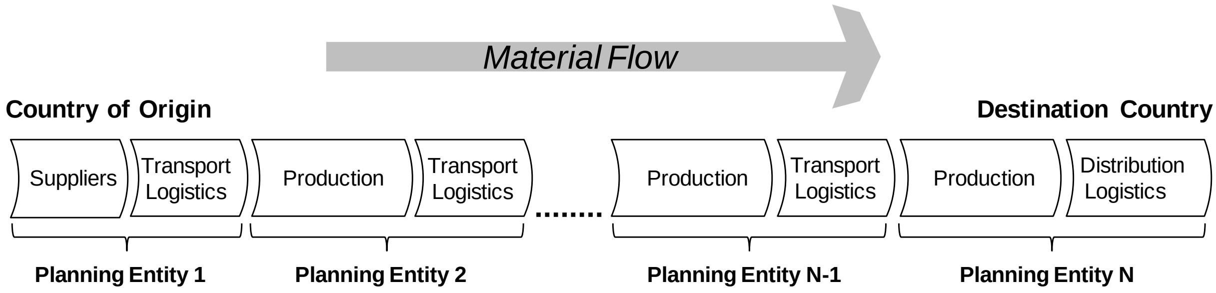

Figure 2 – Chain of planning entities on the operational level (Scholz-Reiter et al., 2009)

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.

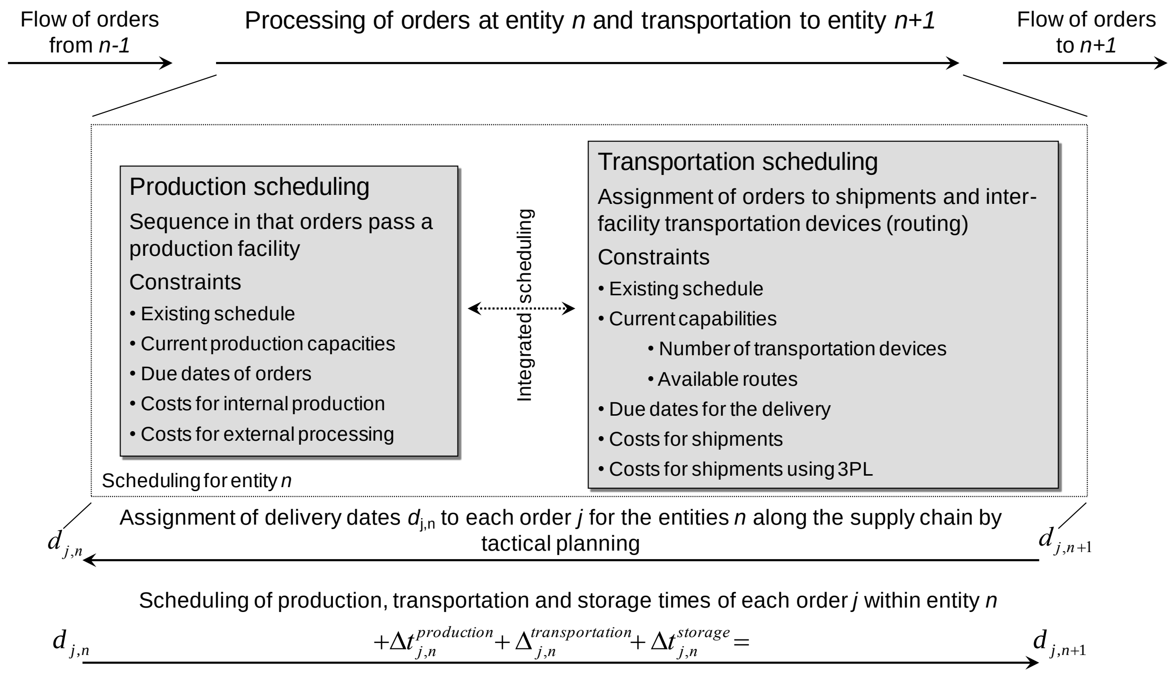

Figure 3 – Scheduling within the planning entities

Since each entity performs the PTSP, they can materialise the competitive advantage provided by the combination of flexibilities of local 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. 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. The interaction among entities will be handle collaboratively by the exchange of due dates.

A scheduling scheme at the operational level needs to be run in successive way. This is motivated by the arrival of new orders, perturbations of resources 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 on the operational level. Also the human aspects that influence the effectiveness of the scheduling are considered in the generic approach. Furthermore, 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 idea applicable to different industries. On the sequence, the mathematical models for the production scheduling and transportation scheduling will be presented.

4. MATHEMATICAL MODELLING

In this section, a mathematical model for the integrated scheduling of production and transportation (PTPS) will be presented. The formulation for the integrated scheduling implements the functionalities of the described generic approach. Furthermore it can be split into two separate mathematical models that are either dedicated to production scheduling or transportation planning. These three mathematical programs are used for the computational analysis in section 5.

A mixed-integer program (MIP) for the operational level that combines the production scheduling of an OEM and the associated vehicle routing for the transportation of orders to final customers is introduced in the following. The MIP 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. 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. The orders can be stored before the first production level, between production levels and before the assigned tour departs. Furthermore, orders can be processed externally in a very short time but causing a comparatively high cost.
An adapted vehicle routing formulation is employed for the transportation scheduling of orders. A new tour can be conducted as soon as a transportation device becomes available. This might be the case when a tour from a preceding production facility arrives or a transportation vehicle returns from its tour to the final customers. All considered tours start and terminate at the OEM location and have a limited transportation capacity. 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. Only a minimal transportation time between two consecutive locations of a tour is enforced. By extending this time, orders can be stocked during their transportation. A late delivery of an order to the customer is penalised. Within a certain tour each location of the transportation network can be visited only once. However, a location can be visited by several tours, in order to deliver different orders. 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 and tours that are on their way to the customers. 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

I	Locations
I^D	Production location; $\left(I^D \subseteq I\right)$
I_v^{SL}	Start location of tour v; $\left(I_v^{SL} \subseteq I\right)$
I_i^s	Connected locations to i; $\left(I_i^s \subseteq I\right)$
J	Customer orders
T	Order types
$T_{j,t}^j$	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^{h}	Storage costs of an order
$c^{p}_{j,t,n,m}$	Processing costs of j at n on m
c^{3pl}	Costs for 3PL
$d_{i,i',v}$	Travel time of v between i and i'
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
$t^{dd}_{i,j}$	Desired delivery date of j at i

Positive Variables

$T^{c}_{j,n}$	Completion time of j at m on n
T^{d}_{j}	Delivery delay of j to the customer
T^{h}_{j}	Storage time of j before $n=1$
$T^{a}_{v,i}$	Arrival time of tour v at location i
T^{dv}_{v}	Duration of tour v
T^{s}_{v}	Start time of tour v

Binary variables

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

$A_{j,v}$ j is assigned to tour v
O_v Tour v is conducted
$Z_{v,i,i'}$ i' is visited after i by tour v
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.

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

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.

$$T_{j,n-1}^c + t_{j,n}^a + \sum_{m \in M_n^e} pt_{j,t,n,m} X_{j,n,m} \le T_{j,n}^c \qquad \left(j \in J; t \in T : j,t \in T_{j,t}^j; n \in N_{j,n}^p\right) \tag{2}$$

$$X_{j,n,m} = 1 \qquad \left(j \in J; n \in N_{j,n}^p; m \in M_n^e \wedge A_{j,n,m}^{mach}\right) \tag{3}$$

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).

$$1 - \left(2 - X_{j,n,m} - X_{j',n,m}\right)M \le Y_{j,j',n,m} + Y_{j',j,n,m} \le X_{j,n,m} \tag{4.1}$$
$$\left(j, j' \in J : j \ne j'; n \in N_{j,n}^p \wedge N_{j',n}^p; m \in M_n^e\right)$$

$$1 - \left(2 - X_{j,n,m} - X_{j',n,m}\right)M \le Y_{j,j',n,m} + Y_{j',j,n,m} \le X_{j',n,m} \tag{4.2}$$
$$\left(j, j' \in J : j \ne j'; n \in N_{j,n}^p \wedge N_{j',n}^p; m \in M_n^e\right)$$

$$\begin{aligned} T_{j,n}^c + pt_{j',t,n,m} \quad \le \quad & T_{j',n}^c \\ & + M(2 - X_{j,n,m} - X_{j',n,m}) \\ & + M\left(1 - Y_{j,j',n,m}\right) \end{aligned} \tag{5}$$
$$\left(j, j' \in J : j \ne j'; t \in T : j,t \in T_{j,t}^j; n \in N_{j,n}^p \wedge N_{j',n}^p; m \in M_n^e\right)$$

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

Since the production capacities are limited the orders can be stored before and between the production levels as well as before the start of the assigned tour. The total storage time is given by equations (7).

$$T^h_j \geq T^s_v - M\left(1 - A_{j,v}\right) - \sum_{n \in N^p_{j,n}} \left(t^a_{j,n} - \sum_{m \in M^e_n} pt_{j,t,n,m} X_{j,n,m} \right) \qquad \left(j \in J; t \in T : j, t \in T^j_{j,t}; v \in V\right) \tag{7}$$

Each order is transported by a tour to the final customers. To this end orders are assigned to a tour. 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.

$$T^c_{j,n} \leq 0 \qquad \left(j \in J; n \in N : N^p_{j,n} = \varnothing\right) \tag{8.1}$$

$$T^c_{j,N} \geq t^a_{j,n} - M(1 - E_j) \qquad \left(j \in J; n \in N\right) \tag{8.2}$$

Equations (9) to (10) define the route of a tour in the case that it is conducted. The tour starts at the considered production facility. In the event that a tour has already departed from the production facility at the time of planning, the previously visited location is considered as starting location. A tour is only considered by the program when at least two route segments remain and an order has to be delivered. Each tour terminates at the production facility.

$$\sum_{i' \in I^S_i} Z_{v,i,i'} = O_v \qquad \left(i \in I^{SL}_v; v \in V\right) \tag{9}$$

$$\sum_{\substack{i \in I: \\ i' \in I^S_i}} Z_{v,i,i'} = O_v \qquad \left(i' \in I^D; v \in V\right) \tag{10}$$

The continuity of route segments of a tour is given by equation (11).

$$\sum_{\substack{i \in I: \\ h \in I^S_i}} Z_{v,i,h} - \sum_{i' \in I^S_h} Z_{v,h,i'} = 0 \qquad \left(h \in I; v \in V\right) \tag{11}$$

Each order is assigned to one tour; partial deliveries are not allowed. In addition it is possible to use a 3PL for the shipping of orders. Hence, the delivery of the order to the customer 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.

$$\sum_{v \in V} A_{j,v} = \left(1 - L_j\right) \qquad \left(j \in J\right) \tag{12}$$

$$A_{j,v} = 1 \qquad \left(j \in J; v \in V : j, v \in A^{tour}_{j,v}\right) \tag{13}$$

A regular tour from the considered production facility to the customers can start as soon as all assigned orders are manufactured and the transportation device is available. In the case that a tour already departed the production facility at the execution time of the planning, the completion time of orders is assumed to be zero as well as the date of availability of the transportation devise. Hence, the tour can be resumed immediately. Furthermore, the departure time for a not conducted tour equals zero.

$$T_v^s \geq T_{j,n}^c - M(1 - A_{j,v}) \qquad (j \in J; n = N; v \in V) \tag{14}$$

$$T_v^s \geq t_v^{av} - M(1 - A_{j,v}) \qquad (j \in J; v \in V) \tag{15}$$

$$T_v^s \leq O_v M \qquad (v \in V) \tag{16}$$

A lower bound for the arrival time of a tour at the first location is given by the departure time from the starting location and the minimal required travel time between the locations. In the event that the tour already departed while the planning is carried out, the travel time is adjusted to a remaining travel time for this tour.

$$T_v^s + d_{i,i',v} - M(1 - Z_{v,i,i'}) \leq T_{v,i'}^a \qquad (i \in I_v^{SL}; i' \in I : i' \in I_i^s; v \in V) \tag{17}$$

Equations (18) and (19) ensure that the arrival time at a consecutive location of a tour is greater than the sum of preceding arrival time and the minimal required travel time. If the planning is carried out while a tour is between two locations the required travel time is adjusted to a remaining travel time for this tour.

$$T_{v,i}^a + d_{i,i',v} - M(1 - Z_{v,i,i'}) \leq T_{v,i'}^a \qquad (i, i' \in I \setminus I_v^{SL} \wedge I^D : i' \in I_i^s; v \in V) \tag{18}$$

$$T_{v,i}^a + d_{i,i',v} - M(1 - Z_{v,i,i'}) \leq T_{v,i'}^a \qquad (i \in I : i' \in I_i^s \wedge i' \in I^D; v \in V) \tag{19}$$

In the case that a location is not part of the tour the arrival time equals zero.

$$\sum_{i' \in I : i \in I_{i'}^s} Z_{v,i',i} M \geq T_{v,i}^a \qquad (i \in I; v \in V) \tag{20}$$

Each tour has a limited transportation capacity. In the case that a tour has already departed while the planning is carried out the transportation capacity of this tour is adjusted to the required capacity of the assigned orders. Hence the tour cannot pickup any additional orders.

$$\sum_j A_{j,v} r_j \leq \bar{r}_v \qquad (v \in V) \tag{21}$$

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

$$\sum_{j \in J} A_{j,v} \leq O_v M \qquad (v \in V) \tag{22}$$

The duration of a tour is greater than zero in the case that the tour is conducted.

$$T_v^{dv} \geq T_{v,i}^a - T_v^s - M(1 - O_v) \qquad (i \in I^D; v \in V) \tag{23}$$

Each order has a desired delivery date. The delivery of an order cannot be early but late.

$$T_{v,i}^a \geq t_{i,j}^{dd} - M(2 - A_{j,v} - O_v) \qquad (i \in I; j \in J; v \in V) \tag{24}$$

$$T_j^d \geq T_{v,i}^a - t_{i,j}^{dd} - M(2 - A_{j,v} - O_v) \qquad (i \in I; j \in J; v \in V) \tag{25}$$

The objective function minimises the costs for delayed deliveries, the processing and storage costs of orders 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.

$$\begin{aligned} Min.\quad & \sum_{j \in J} T_j^d c_j^d + \sum_{j \in J} \sum_{\substack{t \in T: \\ j,t \in T_{j,t}^j}} \sum_{n \in N} \sum_{m \in M_n^e} X_{j,t,n,m} c_{j,t,n,m}^p \\ & + \sum_{j \in J} T_j^h c^h + \sum_{v \in V} \left(O_v c^{fv} + T_v^{dv} c^{dv} \right) \\ & + \sum_j \left(E_j c^{ep} + L_j c^{3PL} \right) \end{aligned} \tag{26}$$

4.4. Mathematical models for the sequential case

The above-introduced formulation of the PTSP combines the mathematical formulation of a production scheduling for a heterogeneous open flow-shop with several consecutive production levels and a vehicle routing problem for the delivery of customers orders. Hence, the modelled characteristics of the given formulation can be captured by separated formulations.

4.4.1. Mathematical model for production planning

The production scheduling can be obtained by combining the following equations. First the sequencing and scheduling of orders is performed by equations (1) to (6). Since, the storage of orders is penalised equation (7) needs to be adapted in a way that externally processed orders are not considered. Externally processed orders are assumed to stick to their assigned due date. The storage time of orders is now given by equation (27).

$$T_j^h \geq t_j^{dd} - M(1 - E_j) - \sum_{n \in N_{j,n}^p} \left(t_{j,n}^a - \sum_{m \in M_n^e} pt_{j,t,n,m} X_{j,n,m} \right) \qquad \left(j \in J; t \in T : j,t \in T_{j,t}^j \right) \tag{27}$$

Furthermore, the scheduling is driven by the given due dates of the orders. These due dates determine the point in time when the orders have to be passed to the transportation system. In the case of a sequential approach the due dates at the interface of production and logistics systems have to be enforced. This means that no late deliveries are possible. Hence, equation (28) states that each order that is processed needs to be finished before the assigned due date.

$$T_{j,N}^{c} \leq t_{j}^{dd} + E_{j}M \qquad (j \in J) \qquad (28)$$

External processing ensures in the case of pure production scheduling as well the feasibility of the model. The objective function minimizes the costs for internal and external production as well as for the storage of orders.

$$\begin{aligned} Min.\ & \sum_{j \in J} \sum_{\substack{t \in T: \\ j,t \in T_{j,t}^{j}}} \sum_{n \in N} \sum_{m \in M_{n}^{e}} X_{j,t,n,m} c_{j,t,n,m}^{p} \\ & + \sum_{j \in J} T_{j}^{h} c^{h} + \sum_{j} \left(E_{j} c^{ep} \right) \end{aligned} \qquad (29)$$

4.4.2. Mathematical model for transportation scheduling

The vehicle routing formulation can also be derived by partly using equations of the introduced PTSP. The interface between the production and transportation system has to be modelled by adding a provision date of orders instead of a completion date of production. This is done by equation (30), where t_{j}^{a} denotes the provision date of an order.

$$T_{v}^{s} \geq t_{j}^{a} - M\left(1 - A_{j,v}\right) \qquad \left(j \in J; v \in V\right) \qquad (30)$$

The storage time of orders, before the assigned tour to the customers starts, needs to be added to the transportation scheduling as a new constraint (31).

$$T_{j}^{h} \geq T_{v}^{s} - t_{j}^{a} - M\left(1 - A_{j,v}\right) \qquad (j \in J; v \in V) \qquad (31)$$

The assignment of orders to tours and the routing of transportation vehicles are carried out by equations (9) to (13) and (15) to (25). The possible usage of 3PL for the delivery of customer orders ensures the feasibility of the vehicle routing program. The objective function minimises the costs for storage of orders before they assigned tour departs, fixed and variable costs of each tour, costs for delayed deliveries and costs for the usage of 3PL.

$$\begin{aligned} Min.\ & \sum_{j \in J} T_{j}^{d} c_{j}^{d} + \sum_{j \in J} T_{j}^{h} c^{h} \\ & \sum_{v \in V} \left(O_{v} c^{fv} + T_{v}^{dv} c^{dv} \right) + \sum_{j} \left(L_{j} c^{3PL} \right) \end{aligned} \qquad (32)$$

5. COMPUTATIONAL ANALYSIS

The generic approach was formalised by a mixed integer program (MIP) for the case regarding the manufacturing and distribution of final products. Now, the formulations of the sequential (PS) Production Scheduling and (TS) Transportation Scheduling and the integrated (PTSP) Production and Transportation Scheduling Problem will be applied to a test case in Germany in order to compare the performance of sequential and integrated approaches. This analysis enhances the understanding about the involved tradeoffs and characteristics of an integrated production and transportation scheduling.

The test case consists of one OEM located in Kassel. The considered factory ships orders of final products to several locations in Germany. The structure of the material flow within the production facility and the structure of the transportation network are shown in Figure 4.

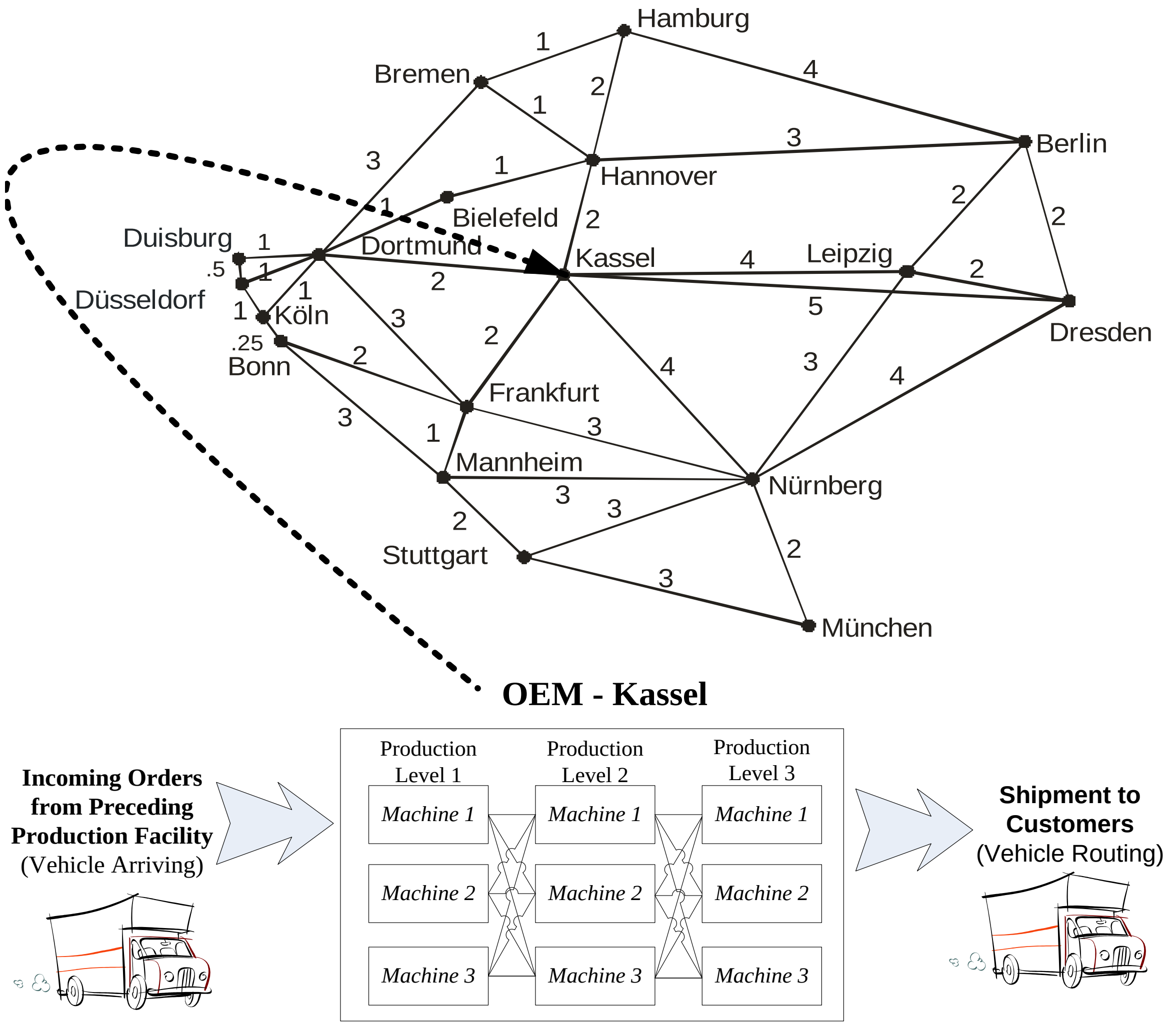

Figure 4 – Structure of the test case scenario

A multi-level production process, which was described by Scholz-Reiter et al. (2005), is carried out at the factory in Kassel. The edges of the transportation network are weighted with the required travelling time between the locations of the network.

The proposed mathematical formulations of the integrated production and transportation scheduling problem as well as the sequential production scheduling and transportation scheduling have 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. Every delayed delivery is charged by costs of 1 per delayed time unit. 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: 2, 10, 18, 26 and 34. At the same point in time new orders become available for the 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: 15.5, 25, 30, 45 and 60. Since the mathematical formulation is a mixed integer problem the instances could be solved by CPLEX 11. The computation was carried out on a 2.67GHz quad-core computer with 4GB of RAM in a deterministic mode of CPLEX with four threads.
The introduced PTSP is dedicated to the operational planning and execution level. This implicates that the program is supposed to be run with a small demand in computational time and several times a day. For instance a re-planning becomes necessary as soon as internal or external perturbations occur or new orders that need to be scheduled arrive. Since the applied formulation of the PTSP is NP-hard only small instances can be solved optimal in a short period of time. This generic result is clearly displayed by the obtained results for the test instances in Table 1.

Table 1 – Gap to the optimal solution after 300 seconds

Transportation devices	**Orders**	**Gap to optimal solution**
1	3	0,00%
1	5	0,00%
2	7	23,00%
2	10	25,15%
3	13	30,21%
3	15	29,29%
4	17	35,78%
4	20	36,67%
5	23	40,06%
5	25	40,74%

The table shows the relative gap between the best integer solution and the best node remaining after 300 seconds of computation. For very small instances the optimal solution can be obtained within this time. Under theses circumstances the program can 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 thereof demonstrated.

Nevertheless very small instances can be used to derive an insight about the involved tradeoffs between the PTSP and the sequential approach of PS and TS. To this end we consider a test case with 2 transportation devices, 5 orders and without storage costs. This setting was used in order to investigate two research questions.

First, the impact of internal and external perturbations on the overall cost was analysed. Two separate examples of these different types of perturbations have been chosen for this analysis. In the first case a breakdown of machine two on production level two was considered as an internal perturbation. In this case the required processing time on this machine becomes quite large.

The behaviour of the different scheduling approaches was studied by a stepwise reduction of the mean values that are used to derive the due dates at the interface of production and transportation. In addition the date of provision for production was adjusted accordingly. The obtained results are shown in Table 2.

Table 2 – Scenario with machine break down

Scenario	Lead-time	**PTSP**	**PS+TS**			Cost comparison
	Manufacturing	Total Costs PTSP	Costs PS	Costs TS	Total Costs PS+TS	
1	10	55	30	25	55	0,00%
2	9	56,5	31,5	25	56,5	0,00%
3	10	62	37	25	62	0,00%
4	9	62	37	25	62	0,00%
5	8	67	42,5	25	67,5	0,75%
6	7	72	48,5	25	73,5	2,08%
7	6	77	54	25	79	2,60%

The first two rows of the table show the results for an undisturbed network. In scenario 2 the lead time for the production of orders was reduced by 1 time unit. Scenarios 3 to 7 relate to the case when machine two on production level 2 was unavailable for manufacturing. Here the lead-time for production was stepwise reduced. As a consequence it could be observed that the PS of the sequential approach was forced to make earlier use of external processing compared to the PTSP. Nevertheless, as soon as the time span between date of provision and desired delivery date to the customers become too small the PTSP has also to make use of external processing or 3PL.

In the second case road works between “Kassel” and “Hannover” have been considered as an example of an external perturbation. This is modelled in the data set by a very large travelling time between these two locations of the transportation network.

The different scheduling results between the two scheduling approaches were again studied by a stepwise reduction of the mean values that are used to derive the due dates at the interface of production and transportation as well as the date of order provision for production. The observed results are shown in Table 3.

Table 3 – Scenario with longer travelling time between Kassel and Hannover

Scenario	Lead-time	**PTSP**	**PS+TS**			Cost comparison
	Transportation	Costs PTSP	Costs (PS)	Costs (TS)	Total Costs	
1	15	55	30	25	55	0,00%
2	14	56,5	30	30	60	6,19%
3	15	57,5	30	31	61	6,09%
4	14	57,5	30	36	66	14,78%
5	13	62,5	30	40	70	12,00%
6	12	67,5	30	45	75	11,11%
7	11	71,5	30	50	80	11,89%

The first two rows of the table are once more related to the case of an undisturbed system but with less time available for transportation. Scenarios 3-7 show the development of total cost for further reduced transportation lead-times in the disturbed case.

Since the dates of order provision are fixed in the sequential scheduling approach the TS needed to make earlier use of 3PL compared to the PTSP, although the possibility of a delayed delivery was given. If the date of order provision for production and the desired customer delivery date provide an adequate time span the PTSP can make use of a different production scheduling that allow affected orders to depart from the OEM location in time.

In general a better performance in regard to costs could be observed by the applied PTSP in comparison to the sequential scheduling approach of PS and TS under consideration of internal or external perturbations. Depending on the given dates of provision and due dates the PTSP achieved on average lower costs by adjusting the schedules and routes in an more efficient way. Furthermore, it can be shown that the costs of the PTSP do not exceed the total costs of the sequential approach.

The second research question that was studied with this scenario deals with the reduction of mean values that are used to derive the due dates of orders between the planning entities. Basically the question is whether it is possible to reduce the lead-time by applying the PTSP instead of a sequential approach? The tactical planning level usually uses mean values in order to align the production and transportation processes. To this end, orders and resources are not considered individually but rather by cumulative mean values. In order to ensure that the operational level is capable of setting up a feasible plan based on the obtained recommendations of the tactical planning level the used mean values are chosen a little bit larger. This adding provides some flexibility to the production and transportation system that for instance can be used to handle perturbations. Since the PTSP integrates the production and transportation system it combines as well the given flexibility of both systems. Hence, it becomes more robust in regard to internal and external perturbations. On the other hand this combined flexibility leads to costs along the supply chain that are mainly driven by storage costs for orders in an undisturbed day to day business. Shrinking the flexibility that is given by the tactical planning level can reduce these costs. Hence the overall lead-time can be reduced. The previously studied scenario also supports this finding. This means that the used mean values at the tactical level can be reduced up to a certain share without compromising the good performance of the PTSP that outperforms the sequential scheduling

approach. Nevertheless the optimal share of reduction that can be obtained needs to be further investigated.
To sum up, our computational analysis indicates two major findings for the PTSP. Costs can be significantly reduced and lead-times can be shortened by properly combining the flexibilities of production and transportation systems.

6. DISCUSSION AND IMPLICATIONS

This paper compared the performance of two approaches for the production and transportation scheduling: the sequential one – currently deployed in Advanced Planning Systems (APS) – and an integrated approach based on the integrated production and transportation scheduling problem (PTPS). The results of the computational analysis demonstrated that the proposed integrative approach for the simultaneous scheduling of manufacturing and transportation systems outperforms the sequential one. Furthermore, this analysis indicates two major findings for the PTSP: (i) costs can be significantly reduced and (ii) lead-times can be shortened by properly combining the flexibilities of production and transportation systems. Even though the outcome is based on mathematical programs with limited capabilities in regard to the number of scheduled orders, it provides solid motivation and support for the forthcoming development of heuristics for integrating manufacturing and transportation scheduling.

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