Terminal operations management in vehicle transshipment

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Abstract

This paper reports on the development of an automated planning and scheduling system supporting terminal operations of the vehicle transshipment hub in Bremerhaven. We describe terminal operations and derive an integral decision model for manpower planning and inventory control. Thereby we propose a hierarchical separation of the integral model into sub-models and develop heuristics to solve the arising sub-problems.

Keywords: Vehicle logistics; Transshipment; Manpower scheduling; Inventory control; Heuristics

1. Introduction

The logistics of finished vehicles has grown impressively during the last decade, leading to the emergence of a world-wide hub and spoke network (Drewry, 1999). Despite high growth rates, the oligopolistic structure of the market has led to a dramatic increase in competition between ports (MarketLine, 1998). Nowadays, ports must face up to market demands and deliver quality service and improved efficiency (Cullen, 1998). To this end the authors have set out to develop a decision planning and scheduling system intended to support terminal operations at the vehicle transshipment hub in Bremerhaven.

Decision-making related to vehicle hub operations can draw on methodological support offered by standard approaches to hub location (Domschke and Krispin, 1997; Racunica and Wynter, 2000), ship routing and scheduling (Ronen, 1993; Fagerholt and Christiansen, 1999; Bendall and Stent, 2001), the design of storage areas (Iranpour and Tung, 1989; Cassady and Kobza, 1998)
and, finally, loading issues (Agbegha et al., 1998; Nishimura et al., 2001). As yet, there has been no methodological support available for vehicle terminal operations of the type already developed for container transshipment (Steenken et al., 1993; Chen, 1999; Böse et al., 2000; Shabayek and Yeung, 2002).

Terminal operations in vehicle transshipment differ significantly from container transshipment, that is typically supported by rule-based control systems. First, container flows are strongly fragmented, whereas vehicle flows have much in common with bulk cargos. Second, containers may be relocated several times during their stay in a hub. Due to the danger of damage resulting to vehicles, the practice of relocation is avoided at vehicle hubs. Third, containers can be stacked upon one another, increasing storage space, whereas vehicles cannot.

In vehicle transshipment, the notion of bulk grouping allows the definition of reasonably sized entities for planning. Since the relocation of vehicles should be kept to a minimum, their assignment to appropriate locations is a matter of importance. Finally, the area taken up by vehicle stocks is enormous, so that the distances to be covered become an important component in the planning process. These findings have motivated the design of a planning and scheduling system, rather than a rule-based control system.

In Section 2 we introduce terminal operations and discuss the planning and scheduling problem as it generally occurs in vehicle transshipment. In Section 3 we present an integral optimization model for manpower planning and inventory control. In Section 4 we consider the hierarchical problem separation and the heuristic solution procedures for the separated sub-problems. Finally we discuss the impact on the system’s efficiency in Section 5, before we conclude in Section 6.

2. Management of the Bremerhaven hub

Bremerhaven is one of the largest vehicle ports in Europe (Herfort, 2002). Its operator, Bremer Lagerhaus Gesellschaft (BLG), handles in excess of 1 million vehicles per year. Balanced ingoing and outgoing traffic produces a high frequency of carrier callings, because vessels regularly discharge and load vehicles in almost equal quantities. Bremerhaven is visited by 1350 deep sea carriers and feeders annually (Kuhr, 2000). Nearly 90,000 vehicles can be stored on 1.6 million square meters, about 500,000 square meters are under cover. For a bird’s-eye view of the terminal see Fig. 1.

Vehicles for export arrive from inland via rail or truck and remain in the terminal only a few days before they are shipped in the majority of cases to the US. Import partly deals with main haul runs, for which the modal shift merely entails a certain slack in the logistic chain. These volumes leave Bremerhaven quickly, either by feeder ship or rail. Another large portion of import vehicles is subject to complex transshipment arrangements. In particular, Far Eastern manufacturers use the terminal as a “buffer stock”, because they have to supply from stock in order to compete with vehicles produced in the EU, which are increasingly “made to order”.

Due to high volume and complexity, operations of the vehicle terminal have thus far been characterized by short-term reaction, rather than planning. As often observed, manual planning tends to result in the inefficient and unreliable implementation of work processes. In order to improve the efficiency and reliability of work processes, a planning and scheduling system has been developed. This system integrates mid-term capacity planning and short-term scheduling.
Applying it on a rolling horizon makes it possible to produce detailed plans for forthcoming work-shifts and identifies capacity bottlenecks at an early stage.

For the purpose of planning, the 90,000 parking slots are divided into 80 storage locations of approximately equal capacity. These locations are referred to as internal locations. Additionally, 60 external locations denoting quays or rail ramps serve as customer transfer points and consequently no capacities are considered, cf. Fig. 2. We refrain from considering actual distances between locations. Instead we consider a productivity measure, i.e. the number of vehicles which can be moved between two locations per unit time. This measure is based on distances, but includes setup times and may even be modified in order to incorporate bottlenecks in the travel way system, etc.

Since transshipment typically also entails an intermediate period of storage, too, vehicles are relocated twice—denoted as storage and retrieval in the following. Avoiding damage to vehicles

![Fig. 1. Bird’s-eye view of the import terminal. In the foreground we can see car-carriers at berthing facilities. Separated from the waterfront by rail and ramps, there are the storage areas and multi-storey facilities. Added value facilities and transshipment points to the hinterland are located in the lower right corner as well as in the background.](image1)

![Fig. 2. Illustration of terminal as considered in the planning and scheduling module. Internal locations represent storage areas of certain capacity, whereas external locations merely represent transshipment points. Locations are connected by a system of travel ways.](image2)
whilst being moved is of top priority. Damage levels between 0.5% and 1.0% of the transshipment volume are acceptable, rates beyond this range are likely to result in the loss of contracts (Drewry, 1999). Due to the risk of damage, manufacturers are unwilling to accept moves other than necessary for storage and retrieval, therefore we can confine ourselves to these two types of movement.

Central to our approach is the notion of a task. A task comprises the relocation of a number of identical (assumed) vehicles which are treated as bulk cargo. The vehicles included in the task are supposed to be transported from an origin to a destination in a given, typically narrow time window. We differentiate between “storage tasks” entering vehicles to the terminal and “retrieval tasks”, performing the vehicle dispatch from the terminal. A pure modal shift consists of two successive tasks comprising the same volume of vehicles. If intermediate storage beyond the planning horizon is required, storage and retrieval tasks are handled independently. The same treatment applies for vehicles to be kept in buffer stocks. Here, a single storage or retrieval task depicts the consolidation into a storage area, or the vehicle commission from a storage area.

Although differently skilled personnel work together in order to perform a task, we focus on the drivers, whose costs are almost proportional to the number of vehicles moved and the distance covered. Therefore, storage locations are assigned to tasks such that the overall distance of storage and retrieval is minimized. Even if equal overall distances are considered, the distribution of storage locations has a significant impact on the manpower usage. In a congested situation, we prefer storage into a nearby location. In this way the utilization of driving personnel is kept low at the expense of a higher driver demand for the future retrieval.

The interdependencies of location assignment and manpower usage on the duration of a task are depicted in Fig. 3. Since the (location dependent) productivity can be substituted by driving personnel and vice versa, a task can be performed in different modes. The choice of modes of performance links location capacity planning and detailed task scheduling into one integral problem.

In order to ensure safe and reliable operations, drivers are grouped into gangs of between 5 and 50 drivers assigned to a dedicated foreman. In this way the choice of modes of performance can pursue the seamless integration of tasks into a gang structure. However, neither the number of

Fig. 3. The duration of a task consisting of 200 vehicles is determined by its volume, its productivity coefficient and its assigned manpower.
gangs per shift nor their size are known in advance. In actual fact, gangs are set up flexibly depending on the characteristics of the tasks to be performed during a shift. Thus, scheduling pursues both determining a gang structure and fitting the tasks into this structure.

Luckily, no upper limit for the usage of manpower has to be taken into account because drivers can be hired flexibly from a port-wide workforce pool. Management aims at avoiding short-term hiring due to the fact that inexperienced drivers tend to increase damage rates. Therefore, besides efficiency issues, an evenly balanced allocation of manpower is pursued.

3. Integrated manpower and inventory management

In this section we present a mathematical model of the integrated planning and scheduling problem. In order to separate input data from variables, we denote the former with capital letters and the latter with lowercase letters. Central figures are the number of time ticks $T$, the set of tasks $A$ and the set of locations $F$. Constraint sets are typically stated by using dynamically generated subsets of $T$, $A$ and $F$. Subsets are expressed by $S$: $condition$, denoting a subset of set $S$ for which $condition$ holds.

3.1. Problem resources

Tasks: For task $j$ a certain number of vehicles $L_j$ is to be moved in a time interval specified by its earliest starting time $EST_j$ and its latest finishing time $LFT_j$. Vehicles of a task are either to be stored ($Y_j = S$) or retrieved ($Y_j = R$). In case of storage $Q_j$ denotes the given origin, whereas in case of retrieval $Z_j$ prescribes the destination. Clearly, the destination of a storage task is subject to search and is therefore modeled as decision variable. The role of the origin of retrieval tasks is not that obvious:

- in case of a coupled transshipment, i.e. storage and retrieval task of a certain number of vehicles fall into the same planning horizon, the origin of the retrieval depends on the destination of the storage task,
- in case of an uncoupled retrieval task, the origin is specified by $Q_j$.

$A$ set of tasks $j \in A$
$L_j$ number of vehicles relocated by task $j$
$EST_j$ earliest starting time of task $j$
$LFT_j$ latest finishing time of task $j$
$Y_j \in \{S, R\}$ denotes type (storage, retrieval) of task $j$
$Q_j$ origin of task $j$ for $j \in A : Y_j = S$
$Z_j$ destination of task $j$ for $j \in A : Y_j = R$
$V_j$ predecessor task of task $j$ for $j \in A : Y_j = R, V_j = \emptyset$ otherwise

If tasks $i$ and $j$ are coupled so that $i$ precedes $j$, then $V_j = i$, $Y_i = S$ and $Y_j = R$. Furthermore for both tasks $i$ and $j$: $L_j = L_i$ and $Q_j = Z_i$. 
**Time:** The terminal operations are performed during separated shifts. There are two shifts per day, and each shift comprises 7.5 working hours. The time is modeled by discrete time steps. Since a resolution of 1/2 h is used, each shift consists of $t_s = 15$ time ticks $t$. Although not limited by the model, in the current implementation, at most 19 consecutive shifts are planned simultaneously. Since shift boundaries are not stated explicitly, a total of $T = 19 \times 15 = 285$ ticks are considered.

- $t$: time ticks for the entire planning horizon, $t = 0, \ldots, T$
- $t_s$: the number of time ticks per shift is set to a prescribed value $t_s$.
- $u$: the shift number of time tick $t$ can be calculated by $u(t) := \left\lfloor \frac{t}{t_s} \right\rfloor$

**Manpower:** The model provides a regular number of drivers $R_u$ on a per shift basis, which is chosen close to, but typically below, the expected demand. Since performing a task requires an administrative overhead, its minimal driver utilization is restricted to a useful number of drivers $R_{\text{min}}$. We can suspect bottlenecks in the traffic system, i.e. bridges crossing rail connections as shown in Fig. 1. Therefore we suppose a decreasing benefit of engaging additional drivers beyond a certain number. Hence we provide a limitation $R_{\text{max}}$ on the number of drivers per task in the model.

- $R_u$: regular manpower (number of drivers) employed in shift $u$
- $R_{\text{min}}$: minimum number of drivers required to perform a task
- $R_{\text{max}}$: maximum number of drivers allowed to perform a task

**Locations:** For internal locations, indicated by a type descriptor $H = \mathbb{I}$, a capacity $K$ and inventory levels $B_i$ are considered. External locations with $H = \mathbb{E}$ serve as transfer points and consequently no capacities or inventory levels are maintained, cf. Fig. 2. Car-carrier operations have to be performed under spatially narrow conditions, therefore a maximal number of simultaneously operating drivers $M$ is specified for a location.

- $F$: set of parking lots $i \in F$
- $H_i \in \{\mathbb{I}, \mathbb{E}\}$ describes type (internal, external) of location $i$
- $K_i$: capacity of internal location $i$
- $B_i$: initial inventory level of vehicles of internal location $i$
- $M_i$: maximal number of drivers working simultaneously in location $i$

**Telemetry:** Productivity $\varphi(i_1, i_2)$ between location $i_1$ and $i_2$ determines the number of vehicle movements between $i_1$ and $i_2$ one driver can perform during a time tick. Analogously, the production coefficient $\varphi^{-1}$ gives the time needed to perform a single vehicle movement (cycle).

- $\varphi(i_1, i_2)$: productivity between location $i_1$ and and location $i_2$ with $i_1, i_2 \in F$.

3.2. Decision variables

**Storage locations:** Only the destination of storage tasks $z_j$ can be subjected to a search. In case of a coupled transshipment, the origin of a retrieval $q_j$ equals the destination of its logical predecessor, i.e. $q_j = zV_j$. For this reason origins are also modeled as (dependent) variables.
Manpower demand: Since the number of gangs and their size differ from shift to shift, we do not model gangs explicitly. Instead the number of drivers utilized in a gang is stored as attribute $p_j$ of its tasks. Thus, all tasks a gang performs during one shift have the same number of drivers assigned to them. Since different gangs can have the same manpower demand, $p_j$ does not suffice to uniquely determine a gang.

Therefore we model a gang as a chain of predecessor relations $n_j$ among tasks. The first task $j$ in the chain with $n_j = \emptyset$ stands proxy for the implementation of a gang with $p_j$ drivers assigned to it. We can derive starting times $s_j$ from a gang chain by assuming left shifted scheduling at the earliest possible starting time. Similarly the completion time $c_j$ of a task is fully determined by its starting time, its locations (which determine the productivity) and its manpower demand.

\[
p_j \in [R_{\text{min}}, \ldots, R_{\text{max}}] \quad \text{number of drivers employed for task } j
\]
\[
n_j \in A \quad \text{predecessor task of } j \text{ in the same gang chain}
\]
\[
s_j \in [0, \ldots, T] \quad \text{starting time of task } j
\]
\[
c_j \in [0, \ldots, T] \quad \text{completion time of task } j
\]

Inventory control: Inventory levels are maintained for each internal location and every time tick. External locations are not considered here, because they are customer-owned and merely serve as transfer points for storage and retrieval tasks. Clearly the modifications of inventory levels depend on the starting- and completion time of the tasks involved.

\[
l_{it} \quad \text{inventory of location } i \text{ at time } t
\]

3.3. Constraints

Temporal constraints: Eq. (1) ensures that the starting- and completion time of task $j$ fall into the same shift, i.e. tasks cannot be processed across shift boundaries. Time windows of tasks are taken into account by Eqs. (2) and (3). In case of coupled tasks precedence relations are considered by Eq. (4).

\[
u(s_j) = u(c_j), \quad \forall j \in A
\]
\[
s_j \geq \text{EST}_j, \quad \forall j \in A
\]
\[
c_j \leq \text{LFT}_j, \quad \forall j \in A
\]
\[
s_j \geq cV_j, \quad \forall j \in A : V_j \neq \emptyset
\]

Gang constraints: Eq. (5) ensures that all tasks of a gang fall into the same shift. Eq. (6) avoids the splitting of gangs by ensuring that no two tasks share the same predecessor. Finally, Eq. (7) enforces that tasks belonging to the same gang have the same number of drivers assigned to them. Hence we can interchangeably use the terms gang and task in the context of manpower requirements.

\[
u(s_j) = u(s_{n_j}), \quad \forall j \in A ; n_j \neq \emptyset
\]
\[
n_j \neq n_k, \quad \forall j, k \in A : j \neq k \land n_j \neq \emptyset \land n_k \neq \emptyset \\
p_j = p_{n_j}, \quad \forall j \in A : n_j \neq \emptyset \
\]

**Manpower constraints:** Eqs. (8) and (9) restrict the number of drivers assigned to a gang. Eq. (10) implements a more intricate constraint on the grouping of drivers into gangs. Drivers may hinder each other while working at the same location (even if they perform different tasks). Thus, the maximum number of drivers simultaneously allowed at location \( i \) can be restricted.

\[
p_j \geq R_{\text{min}}, \quad \forall j \in A \\
p_j \leq R_{\text{max}}, \quad \forall j \in A \\
\sum_{j \in A : q_j = i \land z_j = t} p_j \leq M_i, \quad \forall i \in F, \quad \forall t = 0, \ldots, T 
\]

**Location constraints:** Eq. (11) assigns the prescribed origin for storage tasks as well as for uncoupled retrieval tasks. The prescribed destination of retrieval tasks is assigned by Eq. (12). In case of coupled tasks, a predecessor of the retrieval task exists. Eq. (13) states that the destination of storage equals the origin of retrieval. Furthermore, Eq. (14) restricts the destination of storage tasks to internal locations. In this way the storage into transshipment points is prevented.

\[
q_j = Q_j, \quad \forall j \in A : Y_j = S \lor (Y_j = R \land V_j = \emptyset) \\
z_j = Z_j, \quad \forall j \in A : Y_j = R \\
q_j = zV_j, \quad \forall j \in A : Y_j = R \land V_j \neq \emptyset \\
H_{z_j} = 1, \quad \forall j \in A : Y_j = S 
\]

**Inventory constraints:** Eq. (15) assigns an initial inventory level at \( t = 0 \) to all internal storage locations \( i \). The set of dynamic inventory balance equations (16) maintains the inventory level from \( t = 1 \) to \( T \). Only internal locations \( i \) (\( H_i = 1 \)) are taken into account, such that the \( L_j \) vehicles of storage task \( j \) (\( z_j = i \)) are added at \( t \) (\( s_j = t \)). Conversely, the \( L_j \) vehicles of retrieval task \( j \) (\( q_j = i \)) are subtracted at \( t \) (\( c_j = t \)). This formulation considers each task \( j \) twice by removing vehicles as early as possible from \( q_j \) and by adding them as late as possible to \( z_j \). In this way buffer times are provided in order to avoid traffic jams. Eq. (17) keeps the inventory level within the feasible domain.

\[
l_{0,t} = B_t, \quad \forall i \in F : H_i = 1 \\
l_{t,i} = l_{t-1,i} - \sum_{q_j \in A : q_j = i} L_j + \sum_{z_j \in A : z_j = i} L_j, \quad \forall i \in F : H_i = 1, \forall t = 1, \ldots, T \\
l_{t,i} \leq K_t, \quad \forall i \in F : H_i = 1, \quad \forall t = 1, \ldots, T 
\]

**Completion time:** Eq. (18) determines the completion time of a task dependent on its starting time and duration. The duration of a task depends on the number of driver cycles required and the duration of an individual cycle. The number of cycles is determined by the vehicle volume \( L_j \) and the number of drivers \( p_j \). A non-integer value of \( L_j / p_j \) indicates that only a subset of drivers can be used in the last cycle. The rounding to the next larger integer implements that the remaining drivers may have to wait for their driving colleagues during the last cycle. The duration of an
individual cycle is given by the coefficient $\varphi^{-1}$ which depends on the productivity measure between the associated storage locations. Fractional durations are rounded up to the next time tick.

$$c_j = s_j + \left\lceil \frac{L_j}{P_j} \phi^{-1}(q_j, z_j) \right\rceil, \quad \forall j \in A$$ (18)

3.4. Objective function

Since the tasks are prescribed, solely the manpower requirements can be subject to optimization. A minimization of the total number of drivers summed up over the shifts considered will probably lead to a cost minimal solution. However, an uneven usage of manpower will not comply with the quality issues of operations. From the viewpoint of quality management a leveling of the manpower demand over the shifts considered is preferable. We pursue a combination of both goals by minimizing the deviation of manpower demand from a prescribed (typically low) regular level given by $R_k$ for shift $k$.

$$P_k = \sum_{j \in A: w(x_j) = k \land n_j = \emptyset} p_j$$ (19)

Eq. (19) determines the driver demand $P_k$ for shift $k$. This figure can be easily determined by summing up $p_j$ over a representative task $j$ for each gang ($n_j = \emptyset$ considers the first task of a gang only) which are processed in shift $k$.

$$\min f(z, p, n) = \sum_{k=0}^{u(T)} (R_k - P_k)^2$$ (20)

By taking Eqs. (1)–(18) into account, a solution to the problem is fully determined by an assignment of the decision variables $z_j$, $p_j$ and $n_j$ for all tasks $j \in A$. Eq. (20) minimizes the squared deviation of $P_k$ from $R_k$ over the shifts considered. In this way a unit of a large deviation is penalized more highly compared to a unit of a small deviation. Since the demand $P_k$ is drawn towards $R_k$, a reduction of the sum of the manpower demand is pursued whenever $R_k$ is low (enough). The objective function formulation aims at leveling demand peaks while increasing the overall productivity of the terminal at the same time.

4. Heuristic solution procedure

Due to the stochasticity of the available data, a solution procedure applies in the framework of an iterative decision support system. A human planner is able to modify critical input data interactively—if one only knows about the criticality of the data. Therefore the process of evolving a final solution typically requires a number of successive optimization cycles alternated with data modifications performed by a human planner. This process requires a solution procedure which

1. produces an interpretable state or solution in every optimization cycle,
2. allows for problem refinement during successive optimization cycles,
3. generates solutions as quickly as demanded by interactivity.
We address (1) by firstly checking the input data on a static basis. We avoid infeasibility due to limited resources by introducing an infinitely-sized resource of extremely high costs, i.e. a large storage area with an extremely low productivity with respect to all other locations. Reasons of infeasibility can be analyzed on the basis of assignments to this virtual storage area. Eventually, tasks can even be excluded from being considered in the optimization course, e.g. in cases where future retrieval tasks are known before their dedicated storage tasks become visible.

Concerning (2) we separate the integral model into a mid-term planning model and a short-term scheduling model. A human planner can decide on the number of shifts the detailed scheduling actually covers. In the extreme, one may even omit any detailed scheduling while merely relying on estimates obtained from mid-term planning. Scheduling can then be integrated into the optimization course successively in later cycles. In terms of Schneeweiss (1999) this concept supports both, an organizational hierarchy due to information asymmetries, and a constructional hierarchy, which reduces conceptual and/or computational complexity. The problem separation is presented in detail in Section 4.1.

In order to meet (3) we propose a rule-based heuristic for the mid-term planning problem because the sub-problems generated by the separation are still too complex to be solved exactly. The heuristic starts with a default strategy and adapts its strategy in later phases to the needs of a particular problem instance. Finally, detailed scheduling on a per shift basis is performed by a neighborhood search heuristic. General ideas of both algorithms are sketched in Sections 4.2 and 4.3.

4.1. Hierarchical problem separation

Top-level model: The model decides upon the processing shift \( u(s_j) \) and the storage location \( z_j \). Therefore, constraints Eqs. (1)–(4) are relaxed by considering a single tick per shift only, i.e. \( s_j = c_j = u(s_j) = u(c_j) \). Eqs. (5)–(10) are no longer relevant, because neither gangs nor drivers are considered in the top-level model. Decisions regarding the choice of storage locations must satisfy Eqs. (11)–(14). All decisions to be taken are linked by a shift-oriented relaxation of the inventory constraints Eqs. (15)–(17).

\[
P_k^* = \left[ \frac{1}{t_s} \sum_{j \in A:u(s_j)=k} L_j \varphi^{-1}(q_j, z_j) \right]
\]

Since \( p_j \) is not defined in the top-level model, Eq. (19) is not applicable. Therefore we determine \( P_k^* \) in Eq. (21) to estimate the manpower demand for shift \( k \) by dividing the aggregate “driving hours” by the number of ticks per shift \( t_s \). Since \( P_k^* \) is a lower bound on the actual driver demand \( P_k \), we can still use Eq. (20) as the objective function with the only difference of using \( P_k^* \) instead of \( P_k \).

Base-level model: At the base-level, operations scheduling can be carried out for each shift separately. Scheduling receives the locations \( q_j \) and \( z_j \) and the shift \( u(s_j) \) as input data from the top-level. The temporal constraints Eqs. (2)–(4) apply in their original setting. Furthermore, gang related constraints Eqs. (5)–(7) and manpower related constraints Eqs. (8)–(10) apply. Instead of controlling the inventory in the detailed model, precedence constraints as expressed by Eq. (4) are inserted for all tasks \( j_1, j_2 \in A \) if \( j_2 \) re-uses a certain storage area directly after it has been emptied by \( j_1 \).
Since for the base-level model Eq. (18) applies, Eq. (19) can be used to determine the actual manpower demand $P_k$, i.e. the number of drivers required for the shift. The goal of the base-level problem is to draw $P_k$ as close as possible towards $P/C_k$. This goal can be easily operationalized by minimizing $P_k$. See Fig. 4 for an overview of the problem separation.

**Base-level anticipation:** The validity of the hierarchical separation depends on how well $P/C_k$ approximates $P_k$. If there is a weak correlation only, the top-level model will take unfavorable decisions with respect to the base-level model. According to Schneeweiss (1999), there should be an anticipation of the base-level. We follow Schneeweiss by generating an approximate schedule already at the top-level.

In so doing a time resolution at the tick level is taken into account which allows a partial support of Eqs. (2)–(4). The starting and completion times are set to the prescribed earliest starting times and latest finishing times, i.e. $s_j = EST_j$ and $c_j = LFT_j$. This consideration of task durations at the level of time ticks improves $P/C_k$ to $P/C/C_k$.

On the left hand side of Fig. 5 manpower capacity is treated on a per shift basis in accordance with Eq. (21) of the top-level model. The right hand side shows the estimated number of drivers $P/C/C_k$ obtained by the anticipated schedule construction, which will be considerably closer to $P_k$ compared to $P/C_k$.

Fig. 6 shows the integration of the anticipatory simulation in the two-level solution procedure. The top-level produces $P/C_k$ which is refined by the base-level anticipation to $P/C/C_k$. This cycle can be

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Fig. 4. Scheme of the hierarchical separation into an top-level planning model and a base-level scheduling model to be solved for each shift separately. The top-level model considers a manpower aggregate in terms of driving hours while the base-level model considers the number of drivers directly.

Fig. 5. Scheduling is (partly) anticipated by a deterministic simulation in the top-level model. By considering EST$_2$ and LFT$_1$ at the level of time ticks for shift $k$, the actual manpower demand can be much better estimated.
run several times before the solution (for which $P_k^{**}$ has been determined) is irrevocably passed on to the base-level. On this basis, $P_k$ is generated and finally implemented.

4.2. Solving the top-level problem

The assignment of a storage location to a task alters the inventory level of a certain storage area. Inventory control approaches have a long history and a rich literature. Although the problem under consideration is related to warehousing models (Cormier and Gunn, 1992) and lot sizing models (Haase, 1993), neither of them fit the problem under consideration. The problem of assigning storage locations in automated storage/retrieval systems shows apparent similarities with the problem at hand. Research in this field is targeted at finding reasonable or even optimal policies (Muralidharan et al., 1995).

By stressing its combinatorial nature, the problem can be formulated as an extension to the general assignment problem, see Gavish and Pirkul (1991) for incorporating multiple resources and Laguna et al. (1995) for the consideration of various efficiency levels of performing tasks. Inventory constraints, however, have not been considered yet. Recently Neumann and Schwindt (2000) have modeled inventory constraints as an extension to the concept of cumulative resources known from project scheduling. However, up to now merely small instances can be solved by this interesting approach.

Construction heuristics using priority rule-based control schemes have a long tradition in scheduling (Morton and Pentico, 1993). Since various problem instances may require different control schemes, combined rules have been taken into consideration. Construction heuristics are computationally inexpensive, hence they may be run many times while slightly modifying their control scheme. Schirmer (1998) distinguishes fixed, class-based and adaptive control schemes. We follow the latter suggestion by iteratively adapting the control scheme of a base-procedure with respect to previous runs.

The base-procedure constructs a solution along the time axis by traversing the shifts involved. For each shift the assignment of schedulable tasks is controlled by the parameter $\alpha$. For each assigned task a location is selected by means of the control parameter $\beta$:

1. Schedulable tasks are sorted with respect to their latest permissible finishing shift; in case of a tie, retrievals are preferred to storages, and in case of a second tie, tasks of larger volume are given preference.
(2) For a shift \( k \), all tasks are assigned whose due date has been met already. If available, further tasks of the above sorted list are assigned until the manpower demand \( P_k^{**} \) exceeds an externally given manpower level \( \alpha \).

(3) In order to assign locations, storage areas of sufficient capacity are sorted into \( \bar{c} \) with respect to a decreasing overall productivity. The overall productivity is calculated by multiplying the storage productivity by the total productivity (= storage productivity + retrieval productivity). This measure considers the uncertainty of the future sufficiently well by biasing towards a high storage productivity.

(4) The storage location tied to position \( c_i \) in vector \( \bar{c} \) is selected with Poisson probability 
\[
P_{c_i} = \frac{(e^{-\beta c_i})/c_i!},
\]
where \( \beta \in [0, 1] \) is an externally given parameter. With \( \beta \approx 0 \) the location yielding the highest productivity is chosen, larger \( \beta \) values also consider less favorable location choices.

The way of applying the base-procedure is illustrated for a reasonably sized problem of 19 shifts with 312 tasks. Fig. 7 shows three solutions in different stages of the optimization course. The \( x \)-axis denotes the shift \( k \), whereas the \( y \)-axis depicts the manpower capacity. The number inside a shift-column reports the number of tasks processed in that shift. The number on top of a shift-column reports its anticipated driver demand \( P_k^{**} \).

To balance the manpower demand, it is aimed at moving tasks into earlier shifts by adapting parameter \( \alpha \). On the basis of the initial solution we firstly determine the average of the manpower demand overshooting \( \alpha \). This figure is added to the current \( \alpha \) leading to an improved estimate of the manpower demand of \( \alpha = 175 \) in the example. By running the base-procedure once again, tasks are moved into earlier shifts, resulting in a leveling of the overall manpower demand, cf. Fig. 7(ii).

The extremely high manpower demand of 331 drivers for shift 2 in solution (i) is decreased by moving tasks into shifts 0 and 1 in solution (ii). The adaptation of \( \alpha \) can be refined in further iterations until no improvement is achieved. If time windows are narrow, a further movement of tasks due to an increasing \( \alpha \) may not be feasible, as it is the case (data not shown) for shift 11 in the example. In order to gain further improvements we now consider alternate location assignments by modifying parameter \( \beta \).

The choice of remote locations in shifts with a relaxed manpower demand is by no means a waste of capacity. Rather, distant storage locations are chosen in order to employ the number of regular drivers \( R_k \). In this way central locations of potentially high productivity may be preserved for use in a forthcoming congested shift. This strategy is applied by iteratively increasing \( \beta \) for shifts with \( P_k^{**} < R_k \). The final result obtained can be taken from Fig. 7(iii). Here the driver demand for shifts 7, 8 and 9 increases, whereas the demand of shifts 10 and 11 significantly decreases.

The procedure presented has been proven to produce satisfying results within a few seconds only.
Fig. 7. Example of capacity-oriented operations planning: (i) initial solution obtained for the problem instance, (ii) further improvement is gained by the withdrawal of tasks and (iii) even more improvements are obtained by location modifications.
4.3. Solving the base-level problem

Although, at a first glance, operations scheduling shows apparent similarities with multi mode project scheduling (Brucker et al., 1999), it differs in the objective function pursued and in the minor role of precedence relations to be considered. The introduction of gang constraints requires the consideration of two successive problems. At the upper level, tasks are assigned to gangs, whereas at the lower level the manpower-minimal order of tasks is determined for each gang separately.

Tasks are assigned to gangs by means of a neighborhood search procedure. We consider a maximum number of gangs equal to the number of tasks $N$ involved in a shift. The neighborhood is defined by moving one task into another shift. Since $N$ tasks are considered, the size of the neighborhood is roughly $N^2$. The neighborhood is applied within a standard tabu-search framework (Hertz et al., 1997). An initial solution is obtained by assigning a gang to each task exclusively. Although this is clearly a waste of manpower capacity, this solution is feasible in every case.

The assignment of tasks to gangs does not completely specify a solution, since different task sequences within a gang may still be feasible. Thus, as a sub-problem the manpower-minimal task sequence has to be calculated. Starting from a lower bound of the driver demand a constraint satisfaction problem is iteratively solved while incrementing the number of drivers. The first solution found determines a feasible task sequence with a minimal number of drivers. Every neighborhood move requires the determination of two task sequences. Despite this computational burden the algorithm finds high quality solutions quickly, mainly because good lower bounds exist and sub-problems are tiny.

Fig. 8 presents a fairly good solution for shift no. 2 of Fig. 7(iii) with 31 tasks and an approximated manpower demand of 187 drivers. The tasks are depicted over the 480 min of a shift (x-axis) requiring a total of 190 drivers organized in 9 gangs. This result took a few seconds of computation time only.

![Fig. 8. Example of short-term operations scheduling.](image-url)
5. Impact of automated planning and scheduling

The planning and scheduling system described has been in use for the terminal operations of the vehicle hub in Bremerhaven since January 2001. Now, in 2002 efficiency gains can be reported by comparing productivity measures and transshipment volumes of 2001 and 2002 with the ones of 2000 as the last year of manual planning.

The main challenge of the vehicle hub in 2001 was to cope with an exceptionally high volume of 1193 thousand vehicles (in comparison to 1073 thousand vehicles in 2000). Managing this peak volume by automated planning and scheduling was actually a great success. Generally, an increasing transshipment volume will lead to a decreasing productivity of operations. Despite the increased transshipment volume marginal productivity gains have been achieved by automated planning and scheduling. The average time of a single vehicle storage took 9.21 min in 2000 and was decreased to 9.17 min in 2001. With respect to the retrieval of vehicles, 15.2 min per unit in 2000 has been reduced to 14.8 min in 2001.

After returning to typical load conditions, according to BLG representatives, the productivity, i.e. for import transshipment has been increased to currently 16.3% in comparison to 2000. By emanating from 363 employees of regular driving personnel, this figure will lead to an annual reduction of personnel costs of more than 1 million USD. Michael Reiter, the manager of terminal operations, sees the major contribution to this positive development in the process orientation imposed by the automated planning and scheduling system. System modeling and software implementation have changed the managerial focus from inventory management to transshipment processes, such that currently more than 60% of import vehicles are not relocated beyond the necessary storage and retrieval movements.

Although the system’s functioning has surpassed the operator’s expectations, further improvements seem possible.

Along with the development of the planning and scheduling module, the telemetry has been analyzed by the Institute of Shipping Economics and Logistics (ISL). Substantial effort has been spent on collecting thousands of geo-coordinates of the port via a differential global positioning system. A graphical editor has been developed that is capable of displaying and modifying this enormous amount of geo-data. All these have been necessary prerequisites in order to derive a valid telemetry for optimization. However, estimate-actual comparisons of the productivity can further fine-tune the system over time.

Task data has been made available from the execution system developed by BLG Datасervices, a subsidiary of BLG. Again, a significant effort has been spent from this side to derive aggregated data suitable for planning and scheduling from the vehicle-individual data records received from customers via electronic data interchange (EDI). Moreover, customers tend not to submit EDI records before the data is entirely definitive. Often this is too late for planning and scheduling purposes, hence the early integration of approximate data from the customer’s side is seen as a hallmark for further improvements.

It is up to the human planner to make use of the system’s flexibility. Next to a proper functioning of the user interface, the unswerving belief of the planner that the system will deliver a reasonable solution in every case is of immense importance. Experience will further encourage the planner to entrust planning and scheduling to the automated system. This process has not come to an end yet and therefore further gains can be expected.
6. Conclusion

In this paper we have described the currently evolving hub and spoke network for the transportation of finished vehicles. The increasing volumes of transshipped vehicles call for planning and scheduling support, particularly for large hubs.

In a rolling time horizon, transshipment tasks have to be scheduled that are constrained by inventory capacity and manpower availability. In this paper we have modeled this issue resulting in a complex combinatorial problem.

In the following we presented a separation of this problem into a two-stage hierarchical model. For both stages we have proposed heuristic procedures capable of solving the entire problem in an iterative decision support system. First reports of the practical use of the system are encouraging.

The system allows the integration of customers into the planning process. In this way supply chain oriented negotiations can be supported. Development continuing in this direction will further strengthen the role of Bremerhaven in finished vehicle logistics.

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