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Part feeding at high-variant mixed-model assembly lines

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Abstract The part feeding problem at automotive assembly plants deals with the timely supply of parts to the designated stations at the assembly line. According to the just-in-time principle, buffer storages at the line are frequently refilled with parts retrieved from a central storage area. In the industrial application at hand, this is accomplished by means of an internal shuttle system which supplies the various stations with the needed parts based on a given assembly sequence. The main objective is to minimize the required number of shuttle drivers. To solve this in-house transportation problem, a heuristic solution procedure is developed which is based on the decomposition of the entire planning problem into two stages. First, transportation orders are derived from the given assembly sequence. In the second stage, these orders are assigned to tours of the shuttle system taking transportation capacity restrictions, due dates and tour scheduling constraints into account. Numerical results show that the proposed heuristic solves even large-sized problem instances in short computational time. Benchmark comparisons with Kanban systems reveal the superiority of the proposed predictive part feeding approach.

Keywords Part feeding · Mixed-model assembly lines · Tour-scheduling

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1 Introduction

Originally, assembly lines were introduced for low-cost mass production of technical goods, e.g. automotives, and production systems were designed to handle only one standard product at a time. With the advancement of flexible tools and automated manufacturing equipment, so-called mixed-model assembly lines were developed which are capable of producing a large variety of different models in an almost arbitrary mix. Today, customized product variety is seen as a major competitive challenge in many industries. Specifically in the automotive industry, a huge variety of product options is achieved from one basic model type by introducing a portfolio of optional features which results in a myriad of model variants. For instance, there are theoretically 2^{27} alternative variants of the Mercedes Benz C-series (Röder and Tibken 2006).

The main planning problems associated with high-variant mixed-model assembly line systems in the automotive industry are the following:

- Line balancing: Determine the configuration of the assembly line including the determination of the number and equipment of stations in the line, the assignment of tasks to stations and the takt time at which products are to be launched onto the line.
- Master production scheduling: Assign production orders for individual models to production intervals over a short-term planning horizon of several weeks.
- Production sequencing: Determine the sequence of models for each production interval.
- Material flow control: Ensure the timely release of parts from suppliers and the in-time delivery of parts to the designated stations at the line.
- Resequencing: Reorder the production sequence in case of disruptions, for instance, due to unexpected part shortages.

This paper deals with the material flow control problem for a paced mixed-model assembly line. Since the generation of stocks at the line is highly disregarded, the supply of parts at the designated stations is mostly governed by the just-in-time or the just-in-sequence principle, i.e. the material supply is determined by the given production sequence of the individual models. Although the number of workers in the part feeding process is relatively small in comparison to the number of workers at the assembly line, the part feeding problem is of great economic importance because of the potential savings in labor costs for shuttle drivers and the reduced risk of part supply at the assembly line. The main objective in feeding the parts to the line is to ensure efficiency of the logistical processes, i.e. avoid line stoppages due to part shortages or overflow of part inventories at the assembly line.

A key problem for part feeding according to the just-in-time principle is to retrieve the parts in their respective unit loads (product-specific bins or pallets) from a central storage system, in practice often called “supermarket”, and to assign them to transportation tours for supply at their designated assembly locations. Transportation is usually carried out by shuttles circulating on predefined paths except for bulky material which is supplied by dedicated vehicles. A specific difficulty of part feeding arising in high-variant mixed-model assembly, as found in premium car manufacturing systems, is the high variability of the required part quantities at the various line stations due to the ever changing daily production sequences. Moreover, the exact timing of the material supply is of utmost importance in order to avoid disruptions in the assembly process.

Some industrial manufacturers try to secure a constant usage of parts by use of level scheduling approaches for production sequencing and the installation of pull-systems like Kanban. However, in high-variant automotive assembly the predominant scheduling objective is to smooth out the workload at the line by using mixed-model sequencing approaches, i.e. to develop a detailed model sequence which seeks to reduce the assignment of auxiliary operators at overloaded stations in case of utility work. To solve the associated part feeding problem, we develop a heuristic solution procedure which aims at minimizing the required number of drivers for in-house shuttle tours between the central part storage and the designated delivery locations. Since the classic vehicle routing and vehicle scheduling problems (VRP and VSP) known from the OR literature do not perfectly match the planning problem at hand, we develop a tailored approach which is fairly easy to implement, performs superior to the popular Kanban systems and is extendable to accommodate further application-specific features.

The remainder of this article is organized as follows. In the next section the in-house transportation problem at hand is explained in greater detail and the specific assumptions are defined. This is followed in Sect. 3 by a review of the relevant literature. In Sect. 4 an efficient heuristic solution procedure is presented which generates the shuttle tours for feeding the parts at the line. In Sect. 5 numerical results are presented which demonstrate the practicability of the proposed solution approach. Finally, the general findings of our investigation are discussed and conclusions are drawn.

2 Problem description

The part feeding problem investigated in this paper is illustrated in Fig. 1. We consider a typical paced mixed-model assembly line at which customer-defined models of a specific car-series are assembled. The individual customer options define the part requirements and the given model sequence determines the time slot (takt) at which the parts are needed. At the respective stations a limited number of bins with parts are stored. Shuttles consisting of a tractor and several trailers travel on predefined paths through the assembly plant to deliver bins with parts and to collect empty bins at the stations. Tours start and end at a depot which is located next to the central part storage (the so-called supermarket) where bins with parts are loaded onto the trailers and empty trailers are dropped.

Inspired by the Japanese just-in-time principle which aims at synchronizing the supply of parts with their demand, many automotive plants introduced Kanban-like systems to control the material flow. According to this system, the buffer stock of parts at the stations is monitored and a signal (the “Kanban”) is transmitted showing the need for immediate replenishment of parts. In traditional Kanban systems, this signal is recorded by shuttle drivers when they pass this station. In more advanced

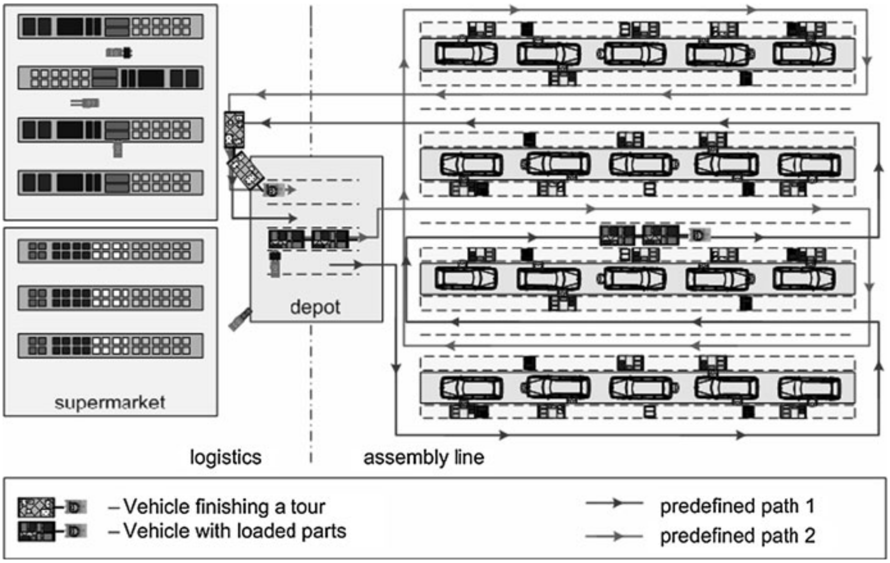

Fig. 1 Assembly line and part feeding principle

systems the signal is transmitted electronically. To supply the parts, usually shuttle tours are established which operate on predefined routes in a constant time interval. The major disadvantage of this kind of Kanban system is that, in case of stock-outs, emergency tours have to be conducted for the supply of the missing parts. As a result, the total demand for shuttle drivers is usually increased. Moreover, Kanban systems appear to be less efficient compared to individually scheduled tours, since part demand is only broadcasted if a critical stock level is reached. This way, the possibility to derive part demand and to determine its exact timing from the given assembly sequence in a predictive manner is ignored.

To overcome the weaknesses of Kanban systems, we developed an alternative approach for feeding parts to the assembly line. This approach relies on the derivation of transportation orders in a predictive manner based on the production sequence of one day or one shift and the customer-specific bill-of-materials for each model in the assembly sequence. This way, tours for the supply of the required parts are generated dynamically based on the predicted transportation orders. The objective is to minimize the number of required shuttle drivers in order to save manpower costs which are considered in practice as the main cost driver in the part feeding process. Moreover, in the long run investment in transportation equipment can be reduced.

Specific assumptions and part feeding characteristics upon which our investigation is based are the following.

- Only one supermarket is established as central part storage while only a limited number of bins is stored directly at the stations.
- The layout of the assembly plant, i.e. locations of stations and the depot, the paths through the assembly plant and travel distances, are given.

- Shuttles travel on predefined paths and carry out specific tours depending on the assigned transportation orders.
- Travel as well as loading and unloading times are deterministic and shuttles do not block each other during a tour.
- All shuttles are identical, i.e. they consist of a given number of trailers each with identical loading capacity and operate at the same speed.
- Parts are supplied in bins of given size. Only fully loaded bins are supplied at a station. No single model requires more parts than can be stored in one bin. A station may receive several bins holding the same or different part types. Each part is assembled only at one single station.
- Idle times of shuttles can occur if a shuttle is waiting at a station to deliver bins with parts. Shuttles may also be idle between tours.
- The maximum number of bins to be stored at a station is given.
- The assembly sequence of models with their individual assignment to time slots (takts) and their customer-specific bill-of-materials are known.
- Disruptions of the assembly or of the part feeding processes are not considered.

The underlying optimization problem can be formulated as a mixed-integer linear program (MILP). For real industrial applications, however, the computational time burden associated with using standard optimization software is prohibitive. Hence, heuristic solution procedures have to be applied.

3 Literature review

A comprehensive overview of supply chain management in the automotive industry is given in Meyr (2004). This work highlights the importance of procurement in cooperation with a widespread network of suppliers, in particular, as production systems in the automotive industry have shifted from a built-to-stock to a customized built-to-order principle with shortened lead times. To manage the variety of parts and to reduce inventories, the just-in-time and just-in-sequence principles have been adopted throughout the automotive industry. Due to the high degree of customized products and the resulting variety of optional parts with short-term demand fluctuations, part-specific supplier capacities have already to be considered at the master production scheduling level (Meyr 2004; Boysen et al. 2009b). Smoothing out the daily part requirements is an issue of considerable importance in the determination of the model sequence at the assembly line (Liu and Han 2008; Boysen et al. 2008, 2009b).

In the academic literature, considerable attention has been given to the mixed-model assembly line balancing problem (Boysen et al. 2009b). In addition, the production sequencing problem has been addressed in a number of publications (Boysen et al. 2009c; Gujjula et al. 2011). However, the part feeding and the corresponding in-house transportation problem have been widely neglected. Specific material flow problems that have been addressed in literature are the determination of storage locations and part feeding policies (Deechongkit and Srinon 2009; Klampfl et al. 2006; Battini et al. 2009) and the choice of the unit load for individual parts from of a given set of container types (de Souza et al. 2008). In their paper, Vaidyanathan et al. (1999) deal with the in-house route planning problem, i.e. the determination of optimal paths through the assembly plant and the corresponding tour schedules. Their approach, however, is confined to a stationary planning environment with given demand rates and shuttles operating at fixed time intervals.

Principally, the control of the material flow between the central part storage and the assembly line can be accomplished by use of push and pull systems. While the push system schedules the supply of parts in a predictive manner, the pull system typically uses Kanban signals to trigger the delivery of parts to the station. Since the introduction of the Toyota Production System, pull systems gained considerable popularity in the automotive industry (Kotani et al. 2004; Yang et al. 2009). Precondition of employing pull systems, e.g. Kanban, is an even demand of each part over a given horizon. Accordingly, so-called level scheduling is applied in order to determine a model sequence which ensures a steady demand of parts over time (Boysen et al. 2008, 2009a, c, d). However, Inman et al. (1997) point out that in practice part consumption rates can neither be even nor nearly smoothed and hence, the objective of level scheduling approaches cannot be fully achieved. More recently, particularly at premium car manufacturers, attention has shifted towards balancing the workload at the line as the huge number of optional features creates a high variability of task processing times. Accordingly, part feeding procedures are necessary which are based on the real model sequence and the exact timing of the part requirements.

This problem is addressed in Choi and Lee (2002) who propose a two-stage heuristic solution procedure. In the first stage, transportation orders are determined based on expected part consumptions rates. Each transportation order refers to an ideal feeding time at which the safety stock level at the station is expected to be reached. In the second stage, these orders are assigned to shuttles which are dynamically routed through the assembly plant. The objective is to minimize transportation time and penalties for deviations of the actual delivery from the ideal feeding time. Though the part feeding procedure developed in Choi and Lee (2002) shares similarities with the problem investigated in this paper, it is not directly applicable here because it makes use of significantly different assumptions and restrictions. For instance, demand peaks for certain parts are not sufficiently addressed and thus material shortages at certain time slots may still occur. Further, possible overflow of part inventories at stations is not considered. The objective in Choi and Lee (2002) is aimed at matching delivery and demand times. Also the approach of Emde et al. (2011) is based on a given production sequence and predetermined supply orders. Their approach, however, is confined to a particular sub-issue, namely the assignment of loads to tours which are operated under a fixed time schedule. Moreover, the objective of Emde et al. (2011) is to simultaneously minimize the total number of bins stored at the line and to harmonize the inventory levels at stations while in our application we develop an integrated approach and directly address labor costs associated with the operation of the shuttle system.

Recently, Boysen and Bock (2011) investigated the problem of just-in-time part supply at a German manufacturer of luxury cars. They consider an in-house part supply problem where parts are stored in a central storage system and supplied to stations arranged in a segmented U-shaped assembly system. For transportation, a combined hoist and fork lift transportation system is used. The objective in their paper is to minimize the maximum inventory of parts at stations in order to minimize the probability of line stoppages. To solve realistic problem instances, they propose a simulated annealing procedure which requires only moderate computational time. Due to the specific assembly and transportation system, e.g. the individual transport of bins, their approach is not directly applicable in a standard assembly line environment where the variability of parts is much higher and usually a number of bins are transported altogether by use of shuttle trains.

The scheduling task of the part feeding problem at automotive assembly plants is similar to the well-known Vehicle Routing Problem (VRP) which dates back to Dantzig and Ramser (1959) and Clarke and Wright (1964). Since a huge variety of VRPs with different attributes is known in the scientific literature, Desrochers et al. (1990) proposed a classification scheme using locations, vehicles, problem characteristics and objectives as the main attributes of a VRP. Surveys on the classic VRP can be found in Laporte (2009), whereas Solomon and Desrosiers (1988) and Cordeau et al. (2002) provide an overview of VRP with time windows and Şen and Bülbül (2008) give a survey on the current state-of-the-art of the multi tour VRP.

In the part feeding problem investigated in this paper, the embedded VRP shows some similarity with the classic VRP, e.g. all tours start and end at a single depot where all the required parts are stocked. Moreover, transportation orders are characterized by their due date, the drop-off location at the line and by the transport capacity requirement assuming a fleet of identical shuttles with limited loading capacity. However, there are major differences to the classic VRP arising from the specific application environment. For instance, the objective is to minimize the required number of shuttle drivers whereas total travel distance and time are secondary. In contrast to the classic VRP, shuttles operate on predefined paths one of which has to be selected for each tour. Independent of the assigned transportation orders, the shuttle follows the entire path. During a day each shuttle conducts a sequence of tours on varying paths depending on the assigned transportation orders. Another major difference is that at each destination (station at the line) the storage space for bins is strictly limited. Finally, application-specific issues have to be incorporated like the generation of transportation orders from the planned mixed-model sequence or the flexibility of time windows for the individual tours.

Furthermore, our part feeding problem shows similarities to vehicle scheduling problems (VSP). Given a set of scheduled tasks with start and ending times and travel times from one task to another, the problem is to find an assignment of tasks to vehicles, so that each task is served by exactly one vehicle and scheduled times are met. The objective is to minimize the costs resulting from this assignment (see Desaulniers et al. (1998) and Bunte and Kliewer (2010) for a detailed description of the VSP and its extensions and Gintner et al. (2005), Löbel (1998), Pepin et al. (2008) and Ribeiro and Soumis (1994) for exact and heuristic solution approaches). Principally, our approach can be transformed into a single-depot vehicle scheduling problem with time windows and special time and capacity constraints

(SD-VSP-TW). In case of an SD-VSP the problem yielding minimum fleet size is solvable in polynomial time using Dilworth's Theorem (Bunte and Kliewer 2010). Note that the SD-VSP-TW can be formulated as a multi-tour VRP with time windows and time constraints, too (Desaulniers et al. 1998). In our application, however, flexible time windows and special time and capacity restrictions apply which do not allow the straight transformation of the problem at hand into a VRP or VSP. Hence, a specifically tailored solution procedure is developed.

4 Solution procedure

As explained before, the key issue of part feeding is to retrieve the parts in their respective unit loads from the central storage and assign them to transportation tours for timely supply at their designated assembly locations. A specific difficulty to solve this problem is caused by the high variability of required part quantities at the various stations. In accordance with industrial applications in the automotive industry, we consider minimizing the number of drivers required to execute the necessary tours as the main objective. To solve this in-house transportation problem, a heuristic solution procedure is developed which is based on the decomposition of the entire planning problem into two stages (see Fig. 2). First, transportation orders are derived from the given assembly sequence. In the second stage, these orders are assigned to tours of the shuttle system taking transportation capacity restrictions, due dates and tour scheduling constraints into account.

4.1 Generation of transportation orders

In the first stage, transportation orders of parts are identified with regard to due date and part code. The given assembly sequence and the model-specific bill-of-

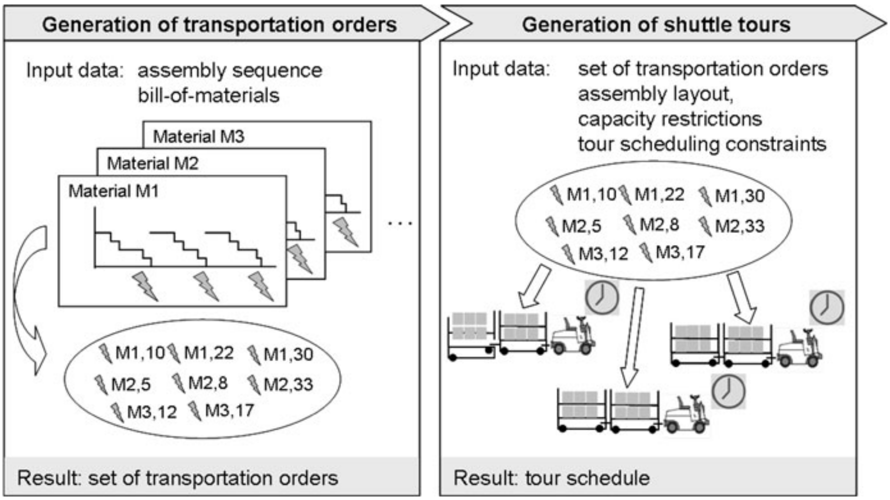

Fig. 2 Problem decomposition

materials imply points in time when the buffer stock of parts at a station is depleted, which directly indicates the due date for replenishment. Since each part is assembled only at one single station, the part code also indicates the respective station at the assembly line and thus the destination of the transportation order. This way, transportation orders $n := (m, dd)$ are generated which identify the respective part m and due date dd. The latter is given by the takt preceding the one at which a part from the newly supplied bin must be available for assembly. Because of lumpy demand figures for optional parts, depletion of the buffer stock at a station may occur at a number of takts before a new unit of the part is needed for assembly. Hence, depletion instances $l := (m, ed)$ of a bin with part m and depletion time (takt) ed, when the last part is removed from the bin, need to be determined as well. The complete algorithm for the generation of transportation orders is outlined in Fig. 3.

4.2 Generation of shuttle tours

In the second stage, transportation orders are assigned to tours of the internal shuttle system taking transportation capacity restrictions and tour scheduling requirements into account. In detail, the generation of tours must observe the following conditions.

- Each transportation order is assigned to exactly one tour.
- The due date of each transportation order is met.
- The storage capacity of each part at the assembly line (in terms of the maximum number of bins) is not exceeded.
- The loading capacity in terms of the usable width of a shuttle and the maximum duration of a tour must not be exceeded.
- Each tour follows exactly one predefined path with given order of stations.

```
Input:   S_m0 - the initial inventory of part m ∈ M
         V_mc - the cumulative demand of part m ∈ M in takt c ∈ C with C := {1,...,|C|}
         Q_m - the unit load of part m ∈ M
Output:  The set of transportation orders N and the set of bin depletions L

foreach m ∈ M do
    nrOrders = 0;
    N := Ø;
    nrDepletions = 0;
    L := Ø;
    foreach c ∈ C do
        if S_m0 +nrOrders · Q_m - V_mc < 0 then
            nrOrders ← nrOrders + 1;
            Generate new transportation order n = (m, c - 1);
            N = N ∪ {n};
        if S_m0 +nrDepletions · Q_m - V_mc ≤ 0 then
            nrDepletions ← nrDepletions + 1;
            Generate new depletion l = (m, c);
            L = L ∪ {l};
return N, L
```

Fig. 3 Algorithm for generation of transportation orders

- Each tour is operated by exactly one driver and each driver must not carry out more than one tour at a time.

Principally, the generation of shuttle tours can be formulated as a mixed-integer linear program (MILP; see the appendix). Since the MILP can be solved to optimality only for extremely small-sized problem instances, it is generally impractical for real-life problem instances due to excessive computational time. Therefore, an efficient two-step heuristic solution approach is proposed which generates the shuttle tours within reasonable time. The composition of this two-step procedure is outlined in Fig. 4. In the first step (tour building), the structural decisions are determined which refer to the assignment of transportation orders to tours, the sequence in which the transportation orders are carried out within the same tour and the choice of a predefined path. The second step (tour scheduling) deals with the scheduling decisions, namely the start and finishing times for each tour, the timing of the unloading operations within a tour and the assignment of a driver for each tour.

4.2.1 Tour building (TB)

In the TB step, transportation orders are assigned to tours such that these tours are as compact as possible, i.e. a tour contains as many transportation orders as possible without violating the given feasibility conditions. The procedure proposed in this paper for use in a serpentine-shaped path layout is derived from the well-known savings heuristic for the classic VRP (Clarke and Wright 1964). In our practical application transparency and adaptability to new constraints is important—the savings heuristic ensures both. The original savings heuristic starts with separate tours for each delivery point and then merges two tours into a composite tour if a saving in total distance is achieved and the loading capacity of the vehicle is not violated. This process is repeated until no more tours can be merged or no more positive saving can be achieved. In our investigation, this procedure is adapted to fit the specific application features. Figure 5 gives an overview of the entire algorithm.

As in the classic savings heuristic, at first each transportation order is assigned to a separate tour. These tours are scheduled to start at the latest feasible time. Additionally, inventory balances for all parts and stations are initialized. Note that this procedure already creates a feasible tour schedule. Next, tours are merged until no more savings can be achieved. In contrast to the original savings heuristic, savings are not based on travel distances, but are extended to include the possible

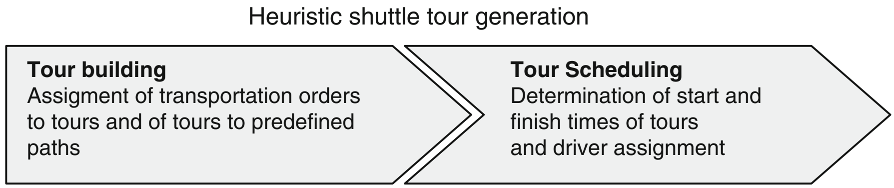

Fig. 4 Two-step procedure for generating shuttle tours

```
Input:    N - The set of transportation orders
          L - The set of depletions
Output:   T - An initial tour schedule

Initialization
    T := Ø ;
    foreach n ∈ N do
        Generate a new tour t for transportation order n;
        Choose a feasible path p∈ P such that the duration dur_t is minimum;
        Schedule t as late as possible;
        Update inventory balances;
        T := T∪ {t};
Merging
    while there are t1; t2 ∈ T so that merge(t1, t2) is a feasible tour and save(t1, t2) > 0 do
        Choose t1; t2 ∈ T so that merge(t1, t2) is a feasible tour and save(t1, t2) is maximum;
        t3 := merge(t1, t2);
        Schedule t3 as late as possible;
        Update inventory balances;
        T := T \ {t1,t2};
        T := T ∪ {t3};
    return T
```

Fig. 5 Algorithm for savings-based tour building

waiting time of the vehicle at a station. Therefore, the savings resulting from merging two separate tours t_1 and t_2 into one composite tour t_3 are determined as $save\ (t_1,t_2){:} = dur_{t1} + dur_{t2} - dur_{t3}$. In order to determine the duration of t_3, the tour is scheduled as late as possible. For the individual unloading operations of the transportation orders backward-scheduling is applied, i.e. the last order in the tour is scheduled at its due date and the preceding orders are appended backwards one-by-one. This procedure determines the latest feasible start time of the tour. Finally, based on this start time forward-scheduling is applied in order to calculate the actual duration of the tour. In each iteration of the savings procedure two tours are selected such that the merged tour is feasible and the savings of the merged tour are maximum and greater than zero. Ties are broken in favor of a minimum difference in tour starting times and secondly of a number of “by-pass stations” within a tour, i.e. stations at which no bins have to be discharged.

4.2.2 Tour scheduling (TS)

In the TS step, the generated tours from the previous step are finally scheduled so that the number of required drivers is minimized. The assignment of transportation orders and its service sequence on a tour remain unchanged in this scheduling procedure. Since drivers have to be employed for an entire work shift, the maximum number of drivers is determined by the maximum number of concurrent tours. Hence, the TS procedure aims at leveling the peak demand for drivers by shifting starting times of tours.

The interval at which a tour can be scheduled is limited due to depletions and due dates at each station. Figure 6 depicts a tour schedule to point out the flexibility of tours. Note, for the sake of simplicity, we only consider one part and fully exhausted initial storage capacities at each station.

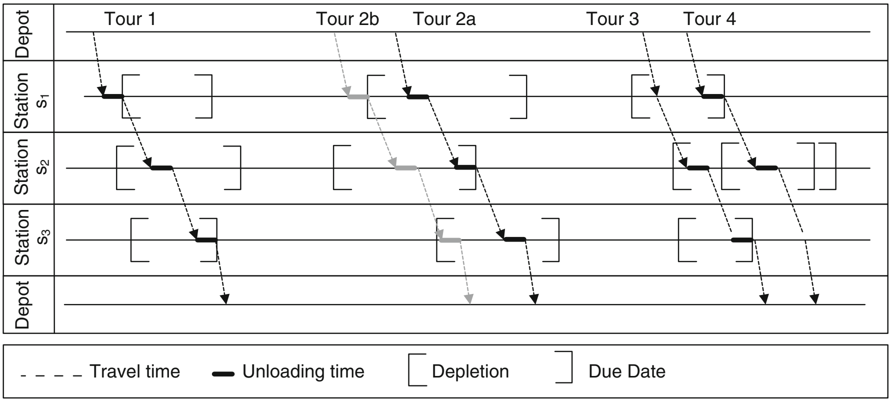

Fig. 6 Flexibility of tours

In the example of Fig. 6, tour 1 starts at the depot and replenishes a bin at station s_1 directly after depletion whereas the bin at station s_3 is supplied at a due date. Apparently, an earlier starting time of tour 1 would extend the tour duration due to additional waiting time at s_1 whereas a later starting time would violate the due date at s_3. Thus, tour 1 provides no flexibility and cannot be shifted from its current starting time. On the contrary, tour 2a is scheduled at the latest possible starting time but provides flexibility to start earlier. Tour 2b depicts the resulting tour if 2a is shifted forward to the earliest possible starting time. Additionally, the flexibility of a tour is further restricted to avoid infeasibilities caused by interferences between tours. If tour 4 would be shifted forward so that the used depletions at station s_2 of tour 3 and 4 are swapped, tour 3 would violate the due date at s_3 since it had to wait for the next depletion at s_2. Therefore, the starting time of tour 4 cannot be shifted so that it uses the depletion of tour 3. In summary, the reasonable time window at which a tour can be executed is limited, because otherwise either a due date will be missed or the duration of the tour would be unnecessarily extended.

For every tour t which has been constructed in the TB step, let l_t be the earliest starting time of the tour and r_t the ending time if it has been started as late as possible in accordance with the considerations from the previous paragraphs. Furthermore, let d_t be the duration of t. $< l_t, r_t, d_t >$ now defines a shiftable interval which can be placed between l_t and $r_t - d_t$. The set of shiftable intervals of all tours defines a shiftable interval graph (Malucelli and Nicoloso 2000) and the task of minimizing the maximum number of concurrent tours corresponds to finding a placement for each shiftable interval such that the maximum clique number of the resulting interval graph is minimum (Cieliebak et al. 2004). This problem is already NP-hard (Malucelli and Nicoloso 2000). Additionally, the placement of an interval can affect other intervals, since this placement, and therefore the scheduling of the corresponding tour at a starting time, affects the available space at stations which might have been considered by other intervals in order to determine l_t.

The tour scheduling algorithm works as follows. It first generates all shiftable intervals and then iterates over them. In each iteration an unscheduled shiftable interval with the lowest flexibility $(r_t - l_t)/d_t$ is chosen and scheduled such that the concurrency with already scheduled intervals is minimum. Afterwards, l_t, r_t and d_t values of the remaining unscheduled intervals are adjusted if necessary and the iteration is repeated until all intervals are placed. Finally, drivers are assigned one-by-one to tours in ascending order of the tour starting time. The entire tour scheduling algorithm is outlined in Fig. 7.

In order to evaluate if an l_t value needs to be changed, a preliminary inventory balance is introduced for each station. Before the first iteration, the preliminary inventory balance considers only the initial inventory and depletions. This means that a negative inventory level can occur. Once an interval has been placed, the transportation orders of the corresponding tour are integrated into the inventory balances and it can be verified if buffer time which has been used to set the value of l_t has been exhausted. Once the tours are scheduled, drivers are assigned to tours without difficulty.

5 Numerical evaluation

The specific research issues addressed in our numerical investigation are the following.

- Does the proposed part feeding approach provide a practical tool for decision support in real applications in the automotive industry, i.e. can transportation schedules be generated within CPU times being acceptable for real-time application?
- How does the proposed part feeding approach perform against a typical Kanban-controlled system which is common in automotive assembly plants?
- To what extent is the performance of the proposed part feeding approach impacted by specific application scenarios, e.g. low versus high variability of parts and the diversity of the assembly processes?

Numerical experiments inspired by observations from real assembly lines employed by European car manufacturers are designed to answer these questions.

Tour scheduling
Initialize preliminary inventory balances;
Generate shiftable intervals I;
while $I \neq \emptyset$ **do**
    Choose $t \in I$ such that $(r_t - l_t) / d_t$ is minimum;
    Find a start time $s_t \in [l_t, r_t - d_t]$ so that the maximum number of parallel tours is minimum;
    Schedule t at s_t;
    $I := I \setminus \{t\}$;
    Update preliminary inventory balances;
    Update l_t, r_t, d_t for non-scheduled tours $t \in I$ if applicable;
Driver assignment
foreach Tour t sorted in ascending orders of the starting times **do**
    Assign next available driver to t;

Fig. 7 Algorithm for tour scheduling

5.1 Experimental design

To evaluate the proposed heuristic planning approach, nine different scenarios have been defined which differ by the size of the problem instances and the degree of part variability (see Table 1). The size of the problem instances is classified as small, medium or large depending on the number of models in the production sequence, the number of assembly stations and the number of parallel line sections into which the entire assembly line is segmented. The arrangement of the line sections basically determines the layout of the assembly system and the associated serpentine paths for the shuttle tours as shown in Fig. 1. Small problem instances with 10 stations, 50 models and one line section are considered as basic test settings while medium (25 stations, 100 models and three line sections) and large instances (50 stations, 200 models and five line sections) represent more realistic conditions.

The second key parameter refers to the variability of parts and thus allows to reflect different degrees of customization and optional equipment. Basically, parts fall into three different categories: common parts have to be assembled into every car; OR-parts are optionally assembled depending on the customer specifications (e.g. components needed for specific electronic assist systems); and XOR-parts represent variants one of which must be used per car (e.g. different gear boxes).

In our experiments, the degree of variability is primarily defined by the fraction of the three different part categories as low, medium and high (see Table 2). In the low part variability instances the distribution of part categories is defined as 70% for common and 15% each for OR and XOR-parts while these fractions are 50 and 25% in the medium and 30 and 35% in the high part variability instances.

Further, we apply the following rules in order to generate the part-station assignment for the different part variability scenarios.

- Each part type is assigned randomly to exactly one station in the line.
- The number of part types assembled at a station is drawn from an integer uniform distribution U[5,8] for the three part variability scenarios.
- For the OR- or XOR-part types the number of variants per part type is drawn from the integer uniform distribution $X = U[2,5]$. Clearly, for common parts there is no such variability.
- For the OR and XOR-parts exactly one variant has to be chosen for assembly at the assigned station. This is accomplished by drawing the variant from the integer uniform distributions U[0,X] and U[1,X] for OR and XOR-parts, respectively.

As shown in Fig. 1, the entire assembly line is segmented into different sections which are arranged in a serpentine configuration. Each station is assigned to a line section such that all line sections are of similar length. The depot is centrally located between the part storage (supermarket) and the line sections. Paths on which the shuttles travel link the part storage to the line segments. There is exactly one path for each line section starting from the part storage, running in clockwise direction to the line segments and returning to the part storage. Data which further specify the layout and the transportation system are summarized in Table 3.

Table 1 Size of problem instances

Small	Medium	Large
50 models	100 models	200 models
10 stations	25 stations	50 stations
1 line section	3 line sections	5 line sections

Table 2 Degree of part variability

Low	Medium	High
70% common parts	50% common parts	30% common parts
15% OR parts	25% OR parts	35% OR parts
15% XOR parts	25% XOR parts	35% XOR parts

Table 3 Specific layout and shuttle data

Station length	10 m
Station width	5 m
Width of the travel path	5 m
Shuttle capacity	2 trailers
Load capacity per trailer	2 m
Shuttle speed	5 m/s
Maximal tour duration	1 h

It is assumed that parts are supplied in pre-defined unit loads (part-specific bins) which differ by the load length occupied on the trailers of the shuttle train. Because of the narrow trailer dimensions no two bins can be stored in a row, i.e. they are placed one behind the other on the trailer. Specific data regarding transportation and part supply are given in Table 4. Data used in our numerical experiments are generated randomly from uniform distributions specified in Table 4.

Because computational times for solving the MILP model presented in the appendix are prohibitive even for the small-sized problem instances, no optimal solutions which could be used as benchmark are available. Hence, heuristic approaches are applied. To solve the part feeding problem in a predictive manner, the heuristic solution procedure presented in Sect. 4 of this paper has been implemented. The first phase of this procedure (tour building, TB) already generates feasible schedules which are improved in the second phase (tour scheduling; TS). For all problem instances, this heuristic approach is benchmarked against a Kanban-controlled system that complies with common part feeding practice in automotive assembly plants.

In a Kanban-controlled part feeding system, shuttles circulate in given time intervals. Once the need for part supply at a station is signalled, a corresponding transportation order is generated and assigned to the next scheduled shuttle tour. In case the loading capacity of the shuttle is exceeded, an emergency tour is created. Two different Kanban timetables are considered with 30 and 60 min interval, respectively.

Table 4 Specific part supply data

Load length of bins	U[0.2, 0.6 m]
Buffer storage per part type at stations	U[2, 5 bins]
Initial inventory per part at stations (R = total part requirement f or the entire production sequence)	U[0.4 R, 0.9 R]
Size of unit load	U[0.5 R, 0.9 R]

For all solution approaches, the number of tours and drivers and the required computational time are recorded. All tests are performed on a PC with Intel(R) Core(TM) i5 CPU with 1.17 GHz and 2.92 GB RAM. For each of the nine scenarios five problem instances were randomly generated.

5.2 Numerical results

The results of the numerical experiments for the nine investigated scenarios are summarized in Table 5. Entries indicate average values over five replications per scenario. As mentioned before, the number of shuttle drivers represents the main performance criterion because this figure directly relates to out-of-pocket costs while the number of tours and their corresponding total length is considered secondary.

Evidently, the heuristic part feeding approach developed in this paper is computationally very efficient. Although the CPU times increase with increasing number of transportation orders, with CPU times less than one second for small sized instances and about 20 s even for large-sized problem instances this approach is well suited for practical application.

The second observation is that the solutions obtained in the first phase of the part feeding procedure (tour building, TB) can be greatly improved in the second phase (tour scheduling, TS) with regard to the number of required shuttle drivers while the total number of tours remains unchanged. This improvement is due to the better time phasing of the individual shuttle tours. On average the number of required drivers is reduced by 34%.

Finally, the comparison with the Kanban-controlled system is very informative from a practical point of view because Kanban-driven part supply dominates in industrial applications. Clearly, the effectiveness of the Kanban approach depends on the density of the shuttle schedule, i.e. the interval at which shuttles depart from the central part storage. Conceptually, the main difference between a Kanban-controlled system and the proposed heuristic approach is that the latter is a proactive system which anticipates the need of part supply at stations due to a predictive generation of transportation orders over a sufficiently long look-ahead period while the Kanban system reacts on replenishment signals not until the buffer stock at a station is depleted. Our experimental results reveal that the proactive approach outperforms the Kanban-controlled systems K30 and K60 for medium and large sized scenarios. The number of required drivers could be reduced on average by 1.47 drivers. As can be seen from the rightmost column of Table 5 the Kanban

Table 5 Overview of test results

Scenario		Result						
Size	Var	TB			TS		K30	K60
		NT	ND	CT	ND	CT	ND	ND
Small	L	2.0	1.6	0.44	1.6	0.04	1 [1]	1 [1]
	M	2.2	2.0	0.54	1.6	0.05	1 [1]	1 [10.8]
	H	2.6	2.0	0.51	1.6	0.05	1 [1]	1 [9.8]
Medium	L	5.4	3.2	2.56	2.0	0.11	3 [0]	3 [0.8]
	M	6.0	3.0	2.84	1.8	0.12	3 [0]	3 [0.8]
	H	5.8	3.0	2.57	2.0	0.08	3 [0]	3 [4.6]
Large	L	9.8	4.4	16.27	2.0	0.28	5 [0]	5 [6.6]
	M	11.2	4.8	21.05	2.0	0.32	5 [0]	5 [15.8]
	H	10.8	4.4	20.34	2.0	0.28	5 [0]	5 [18]

Var part variability, *L* low, *M* medium, *H* high, *TB* tour building, *TS* tour scheduling, *K30* Kanban with 30 min interval, *K60* Kanban with 60 min interval, *NT* number of tours, *ND* number of regular drivers [number of extra drivers], *CT* computational time (s)

system with 60 min interval requires a considerably higher number of extra drivers compared to the 30 min interval. This result clearly shows the sensitivity of the Kanban system to the shuttle frequency.

In summary, the proposed part feeding heuristic is able to provide good quality solutions in very short computational time. Due to the complexity of the underlying vehicle routing problem, optimal solutions are not even available for small-sized problem instances.

6 Summary and conclusions

This paper deals with the problem of in-house part supply from a central storage area to the various stations of a mixed-model assembly line. Our investigation was motivated by applications from the automotive industry, in particular, by the assembly of premium cars, which show a considerable variability in parts requirements. Automotive manufacturers seek to accomplish the part feeding process in a most economical way by minimizing the number of drivers required to operate the shuttle vehicles. This is in contrast to most of the vehicle routing literature which primarily addresses the minimization of vehicles travel times or distances.

To solve the part feeding problem an efficient solution procedure was developed which decomposes the entire planning problem into two stages. After identifying the transportation orders by part code, delivery location and due date, tours of the in-house shuttle system were generated and scheduled such that the peak demand for shuttle drivers was minimized. Since the underlying optimization problem is of considerable numerical complexity, standard optimization solvers are not able to provide solutions to real life problem instances within reasonable time whereas the proposed heuristic solves even large-sized problem instances with only limited computational effort. Future research may be focused on computational improvement, for instance by using heuristics from vehicle scheduling theory or utilizing upper and lower bounds resulting from the Dilworth theorem.

In a practical application the proposed part feeding approach is supposed to be used as a planning step subsequent to the determination of the mixed-model assembly sequence. Integrating the proposed part feeding approach into the entire planning system not only promises cost savings in terms of the number of employed drivers and vehicles, but also reduces the risk of line stoppages due to material shortages which is even more important in a high-variant mixed-model assembly system.

Appendix: Mixed-integer liner optimization model

Sets

S	The set of stations at the assembly line
M	The set of parts
N	The set of transportation orders including two dummy orders representing the start and end order of a tour
P	The set of predefined paths through the plant
D	The set of drivers
T	The set of possible tours of a shuttle with $T := \{0, \cdots, t^{\max}\}$ including dummy tour 0
$N^{Del} \subseteq N$	The set of real transportation orders
$N^{ms} \subseteq N$	The set of transportation orders delivering part $m \in M$ to station $s \in S$
$N^{p} \subseteq N$	The set of transportation orders which can be delivered on path $p \in P$
$M^{s} \subseteq M$	The set of parts assembled at station $s \in S$
$L^{ms} \subseteq L$	The set of part-specific bins which are used to transport part $m \in M$ to station $s \in S$
Q^{ms}	The set of accumulated part-specific bins of part $m \in M$ at station $s \in S$
$T^{real} \subseteq T$	The set of real tours with $T = T^{real} \cup \{0\}$

Parameters

pt_n	The processing time of transportation order $n \in N$
dd_n	The due date of transportation order $n \in N$
w_n	The width of one part-specific bin of transportation order $n \in N$
s_n	The respective station of transportation order $n \in N$
$conn^D$	The time needed to connect and disconnect a trailer to and from the shuttle
$capa^D$	The available width of a shuttle
$tt_{ps_1s_2}$	The travel time from station $s_1 \in S$ to station $s_2 \in S$ on path $p \in P$
$succ_{ps_1s_2}$	is equal to 1 if station $s_2 \in S$ is successor of station $s_1 \in S$ on path $p \in P$
ss_l	The point in time when the stock of parts in bin $l \in L$ is depleted
$L^{\max}_{ms}$	The maximum number of part-specific bins of part $m \in M$ at station $s \in S$

ii_{ms}	The initial inventory of part $m \in M$ at station $s \in S$
$td^{\max}$	The maximum duration of a tour
$N^{ms}[j]$	The transportation order which is the j-th element of the set N^{ms}
$L^{ms}[j]$	The depletion corresponding to the j-th element of the indexed set L^{ms}
$Q^{ms}[j]$	The number of delivered bins defined by the j-th element of the index set Q^{ms}
$bigM$	Big number
$[A,Z]$	The planning horizon

Variables

x_{pdt}	Binary variable which is set to 1 if and only if driver $d \in D$ on his/her tour $t \in T$ is assigned to path $p \in P$
$z_{n_1 n_2 dt}$	Binary variable which is set to 1 if and only if transportation order $n_2 \in N$ is directly processed after transportation order $n_1 \in N$ on tour $t \in T$ executed by driver $d \in D$
st_n^N	Continuous variable which represents the start time of unloading transportation order $n \in N$
st_{dt}^T	Continuous variable which represents the start time of tour $t \in T$ executed by driver $d \in D$
ft_{dt}^T	Continuous variable which represents the finishing time of tour $t \in T$ executed by driver$d \in D$

The MILP model formulation is given as follows:

$$\min \sum_{p \in P} \sum_{d \in D} x_{pd1} \tag{1}$$

$$\sum_{d \in D} \sum_{t \in T^{real}} \sum_{n_2 \in N} z_{n_1 n_2 dt} = 1 \quad \forall n_1 \in N^{Del} \tag{2}$$

$$\sum_{n_2 \in N} z_{n\, n_2 dt} = \sum_{n_1 \in N} z_{n_1 n dt} \quad \forall\, n \in N^{Del}, d \in D, t \in T^{real} \tag{3}$$

$$\sum_{p \in P} x_{pdt} \le 1 \quad \forall d \in D, t \in T^{real} \tag{4}$$

$$st_n^N + pt_n \le dd_n \quad \forall n \in N^{Del} \tag{5}$$

$$\begin{aligned} st_{n_1}^N + pt_{n_1} + \sum_{p \in P} \left(x_{pdt} \cdot tt_{ps_{n_1} s_{n_2}} \right) - st_{n_2}^N \le (1 - z_{n_1 n_2 dt}) \cdot bigM \\ \forall n_1, n_2 \in N^{Del}, t \in T^{real}, d \in D \end{aligned} \tag{6}$$

$$\begin{aligned} st_{dt}^T + \sum_{p \in P} \left(x_{pdt} \cdot tt_{ps_1 s_{n_2}} \right) \\ - st_{n_2}^N \le (1 - z_{1 n_2 dt}) \cdot bigM \quad \forall n_2 \in N^{Del}, t \in T^{real}, d \in D \end{aligned} \tag{7}$$

$$ft_{dt}^T + conn^D - st_{d(t+1)}^T \le \left(1 - \sum_{p \in P} x_{pd(t+1)} \right) \cdot bigM \quad \forall d \in D, t \in T | t < t^{\max} \tag{8}$$

$$st_n^N + pt_n + \sum_{n_1 \in N} \left(x_{pdt} \cdot tt_{pn1} \right) - ft_{dt}^T \leq (1 - z_{n1dt}) \cdot bigM \quad \forall d \in D, t \in T^{real}, n \in N^{Del} \tag{9}$$

$$st_{d0}^T = A \quad \forall d \in D \tag{10}$$

$$ft_{d0}^T = A \quad \forall d \in D \tag{11}$$

$$ft_{dt}^T \leq Z \quad \forall d \in D, t \in T^{real} \tag{12}$$

$$ft_{dt}^T - st_{dt}^T \leq td^{\max} \quad \forall d \in D, t \in T^{real} \tag{13}$$

$$\sum_{p \in P} x_{pdt} \geq \sum_{p \in P} x_{pd(t+1)} \quad \forall d \in D, t \in T^{real} | t < t^{\max} \tag{14}$$

$$z_{n_1 n_2 dt} \leq \sum_{p \in P} x_{pdt} \cdot succ_{ps_{n_1} s_{n_2}} \quad \forall n_1, n_2 \in N^P, d \in D, t \in T^{real} \tag{15}$$

$$\sum_{n \in N} z_{1ndt} = \sum_{p \in P} x_{pdt} \quad \forall d \in D, t \in T^{real} \tag{16}$$

$$\sum_{n \in N} z_{n|N|dt} = \sum_{p \in P} x_{pdt} \quad \forall d \in D, t \in T^{real} \tag{17}$$

$$\begin{gathered} st_{N^{ms}[j]}^N + pt_{N^{ms}[j]} \geq ss_{L^{ms}[j]} \\ \forall s \in S, m \in M^s, i \in 1 \ldots |L^{ms}|, \\ j \in 1 \ldots |N^{ms}| \, | \, Q^{ms}[j] + ii_{ms} - i \geq L_{ms}^{\max} \end{gathered} \tag{18}$$

$$st_{n_1}^N \leq st_{n_2}^N \quad \forall s \in S, m \in M^s, n_1, n_2 \in N^{ms} | dd_{n_1} < dd_{n_2} \tag{19}$$

$$\sum_{n_1 \in N^P} \sum_{n_2 \in N^P} z_{n_1 n_2 dt} \cdot w_{n_1} - capa^D \leq \left(1 - \sum_{p \in P} x_{pdt} \right) \cdot bigM \quad \forall d \in D, t \in T^{real}, p \in P \tag{20}$$

$$x_{pdt} \in \{0, 1\} \quad \forall p \in P, d \in D, t \in T^{real} \tag{21}$$

$$z_{n_1 n_2 dt} \in \{0, 1\} \quad \forall n_1, n_2 \in N, d \in D, t \in T^{real} \tag{22}$$

$$st_n^N \in R^+ \quad \forall n \in N^{Del} \tag{23}$$

$$st_{dt}^T \in R^+ \quad \forall d \in D, t \in T \tag{24}$$

$$ft_{dt}^T \in R^+ \quad \forall d \in D, t \in T \tag{25}$$

A tour is defined by a driver and the number of his/her possible tours. If a driver executes his/her first tour, he/she needs to be considered in the objective function. The objective function (1) minimizes the number of shuttle drivers required to complete all tours. Constraints (2) and (3) are logical constraints which ensure the succession of transportation orders. According to (4) at most one path is assigned to each tour and driver. Constraint (5) ensures that each transportation order is completed on time. The succession of tours is expressed in (6) and (7). Driver schedules are reflected by (8). The finishing time of a tour is determined in (9). In (10) and (11) dummy tours at the beginning of the planning horizon are scheduled for each driver. All tours must be finished within the planning horizon (12). Constraint (13) ensures that maximum tour durations are not exceeded. Constraints (14) enforce a driver-tour assignment to zero, if its previous tour is empty. In (15) the successor relations of two transportation orders are set according to the chosen path of the tour. Dummy transportation orders at the beginning and the end of a tour have exactly one preceding and succeeding transportation order, respectively (16) and (17). Constraint (18) ensures that maximum storage capacities at the stations are not exceeded. Transportation orders are consecutively scheduled according to their due dates (19). Constraints (20) reflect the maximum shuttle capacities. Finally, variable domains are defined in (21–25).

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