Delivery Time Coordination at Customer Sites with Implicit Time Windows – A Computational Evaluation

BY JÖRN SCHÖNBERGER, DRESDEN

1. Introduction

Transport services connect the different locations in a value chain and realizes the physical flow of materials. As a consequence of the high level of labor share among partners in (global) value chains, transport services become more and more important in the business-to-business (B2B) sector. Due to the significant grow of online retail businesses and related internet-based retailing ideas transport services become also more important in the business-to-consumer (B2C) branch. Both the B2B sector as well as the B2C sector offer multi sourcing options where (different) products are bought from different sources (Agrawal et al., 2002). This results in a fragmented flow of goods since different lots and/or parcels are shipped independently from other lots and/or parcels from different supply site to a common customer site. This delivery site is visited several times per period. In the B2B setup, a coordination of the visiting operations becomes necessary in order to ensure that internal downstream processes fit with the (external) transport processes. Furthermore, setup as well as cleaning costs associated with the used handling tools increase if the multiple delivery operations remain uncoordinated here. In a B2C sector it is necessary to coordinate multiple visits at one customer site in order to increase the chance to realize the handover of shipments in a first attempt but to avoid costly and environmental critical re-visits.

The aforementioned challenge of coordination of delivery times belongs to the class of operational fleet management dispatching problems (Crainic and Laporte, 1998) in which the portfolio of requests to be fulfilled is known. Here, the decision about the short term routing of vehicles forming a fleet is addressed. Vehicle routing problems (Golden et al., 2008) like the capacitated vehicle routing problem (CVRP) or the pickup and delivery problem (PDP) represent the core decision tasks in the field of operational fleet management.

Anschrift des Verfassers:
Prof. Dr. Jörn Schönberger
Dresden University of Technology
"Friedrich List" Faculty of Transportation and Traffic Sciences
01062 Dresden

joern.schoenberger@tu-dresden.de

Approaches to achieve a time-coordination between (several) delivery operations and downstream internal processes at a common customer site are based on time windows. An explicit time window determines a period in which an unloading operation at a customer side may start. However, a time window represents a very strict delivery time restriction that is often unnecessarily restrictive. In this article we investigate so-called *moveable* or *implicit time windows* to achieve the aforementioned coordination between several inbound transport processes and downstream processes at a customer. Instead of specifying an absolute position for the delivery operation on the time axis as done by defining an explicit time window, the operation starting times associated with the necessary customer visits are groups together in an a priori unspecified period of the time axis. Only the length of this time window is given as part of the dispatching scenario but not its absolute position on the time axis. Practically, an implicit time window specifies an upper bound on the difference of the starting times of different operations at a commonly served customer site.

Offering implicit time windows to customers can be a competitive advantage of a distribution company that must deliver customer locations twice or even more often during a planning period. However, the consideration of implicit time windows represents a sophisticated challenge for the fleet dispatcher since several unloading times (of different vehicles) require a coordination during the dispatching of the necessary vehicle operations. Waiting times as well as deviations from least distance vehicle routes might become necessary to meet the implicit time windows. In order to contribute to a better understanding of the benefits and challenges related to the consideration of implicit time windows in operational fleet dispatching we are going to find answers to the following two research questions in this article:

1. How can the consideration of implicit time windows into state-of-the-art fleet disposition tools be realized?
2. What are the impacts of the consideration of implicit time windows on the formation of vehicle routes with respect to additional travel distances and additional vehicles needed?

With the goal to find answers to the aforementioned questions we evaluate results from computational experiments. In these experiments we simulate the disposition of a vehicle fleet. The disposition situation is similar to the CVRP scenario but each customer must be visited twice by two different vehicles (each delivering only one specific commodity). A maximal time difference between the necessary two visits must be respected at each customer site. We introduce a dispatching procedure that generates high quality solutions for this dispatching problem by constructing and improving solutions of a model of the disposition problem proposed in Schönberger (2015).

We present the investigated fleet disposition scenario in Section 2. Section 3 describes central aspects of the disposition system used in the simulation experiments. Experimental results are presented and analyzed in Section 4.

2. A Fleet Dispatching Scenario with Multiple Customer Site Visits Coordinated by Implicit Time Windows

The consideration of implicit time windows in fleet management and vehicle routing comes along with additional challenges compared to the consideration of explicit time windows. Therefore, it is necessary to carefully introduce into the concept of this coordination scheme. Subsection 2.1 contains a survey of research related to the consideration of multiple visits at a customer site and their coordination. Subsection 2.2 introduces the fleet management scenario with implicit time windows discussed in the remainder of this article. Subsection 2.3 compares the coordination of multiple visits by implicit time windows with other time window based coordination approaches. Subsection 2.4 summarizes opportunities to achieve and ensure feasibility with respect to implicit time windows.

2.1 Literature

Golden et al. (2008) survey contributions and research directions on the vehicle routing problem class. Problems in which individual pickup and/or delivery locations are considered are investigated and classified by Parragh et al. (2008).

Vidal et al. (2012) write about models and algorithmic approaches on a broader class of vehicle routing problems with several depots. Crevier et al. (2007) report about a variant of the vehicle routing problem in which vehicles are replenished at different re-filling depots while being on route. Cattanuzza et al. (2014) investigate the multi trip vehicle routing problem in which only small vehicles are allowed to enter a downtown area so that a regular return to a depot to refill a vehicle becomes necessary. Goel and Meisel (2013) propose a decision support tool for a vehicle deployment problem in which operations of different vehicles at different locations are coupled by a scheduling constraint.

Differences between routing problems with only one and with several commodities are revealed by Archetti et al. (2014). The split of demand associated with a request in the context of vehicle routing is addressed by Archetti and Speranza (2008).

A general discussion of different types of synchronization constraints in the context of vehicle routing is contributed by Drexl (2012).

The usage of time windows for the coordination of internal processes at a customer site with the delivery times decided by the fleet dispatcher is investigated by Solomon (1987). de Jong et al. (1996), Favaretto et al. (2007) as well as Breier (2015) discuss situations in which the dispatcher has the choice among two or even more alternative time windows at a customer location.

Doerner et al. (2008) report a vehicle routing problem in which sensitive blood products must be collected. In the reported application, a blood collection site must be re-visited several times in order to ensure that the meanwhile collected blood can be processed without deterioration. The concept is quite similar to an implicit time window since the first visit of a location sets limits for subsequent visits. The authors refer to this scenario as a vehicle routing problem with interdependent time windows.

2.2 Dispatching Problem Description

We consider the fleet management scenario introduced in Schönberger (2015). In this scenario the distribution of two types of commodities, A and B, is addressed from the perspective of a trucking company. The trucking company must fulfill transport requests with its own fleet. A transport order comprises the fulfillment of demand of both commodities. Each commodity requires a specially fitted vehicle. Therefore, two types of vehicles are maintained and compose the fleet that is deployed in order to cover the supply demand.

Each of the n_A type-A vehicles can be used to transport only one or several pieces of commodity A and each of the n_B type-B vehicles is able to carry one or several pieces of commodity B only. There are no vehicles that can carry both types of commodities.

All commodities to be distributed are stored at the warehouses WH-A as well as WH-B. The first mentioned warehouse stocks only commodity A but commodity B is exclusively stored at WH-B. Each customer order comprises two transport requests r^A as well as r^B (origin-to-destination requests, for short: od-requests). Request r^A expresses the need to transport a certain quantity of commodity A from warehouse WH-A to a customer location. Similarly, request r^B expresses the need to transport a certain quantity of commodity B from warehouse WH-B to the same customer location specified in r^B.

There is a scheduling requirement that prevents the decomposition of the vehicle routing problem into a type-A routing problem as well as into a type-B routing problem. The delivery operations associated with the two requests of an order must not differ by more than δ time units. A decomposition of the outlined vehicle routing problem into two individual one-commodity-routing problem is therefore inappropriate.

The trucking company has to determine routes for the vehicles so that the total sum of travel distances across the fleet is minimized while the aforementioned implicit time window condition is met. Furthermore, no vehicle route is allowed to last longer than MS^{max} time units (maximal allowed makespan) This decision problem is called the two-commodity capacitated vehicle routing problem with synchronization (2-CVRP-S).

2.3 Operation Starting Time Coordination

It is necessary to ensure that both unloading operations associated with an order are scheduled so that their starting times do not differ more than δ time units. This condition has to be formalized in order to prepare the computer-supported fleet disposition.

2.3.1 Explicit Time Windows

An explicit operation time window is an interval $T\ := [e_O;l_O]$ of the time axis limited by an earliest allowed starting time e_O of an operation O and by a latest allowed operation starting time l_O for this operation. Explicit time windows are often used in the context of vehicle routing, i.e. in the Vehicle Routing Problem with Time Windows (VRPTW) investigated for example by Solomon (1987) or in the Pickup and Delivery Problem with Time Windows (PDPTW) survey by Parragh et al. (2008). Time windows are typically defined in order to enforce that a certain unloading happens within a certain time period.

Consider now a situation with only one unloading operation O and let st_O denote the determined starting time of operation O so that $st_O \in T$. Here, the consideration of the time window enforces the operation starting time into the specific interval on the time axis so that internal upstream or downstream process comply with the unloading operation. Figuratively spoken, the time window consideration enforces the operation starting time to be positioned within a pre-specified part of the time axis (*position restricting property of a time window*).

Assume now two different unloading operations P as well as Q. These two operations are contained in two different routes executed by different vehicles. In case that both operations are scheduled with the interval T then it is sure that the operation starting times of the two aforementioned operations do not differ more than l_O-e_O time units (*difference restricting property of a time window*).

In order to ensure that the two unloading operations are started with a time difference of not more than δ time units it is possible to define a time window $[t_O; t_O+\delta]$ and to ensure that both associated operation starting times fall into this time window. Immediately, the question about an adequate value for t_0 arises. Actually, every t_0-value leads to a time window that implies the fulfillment of the maximal operation starting time difference restriction. The absolute positions of the two operation starting times on the time axis are irrelevant here. It is sufficient to exploit the difference property of the time window but it is not necessary to fulfill the position property of this time window. In conclusion, an explicit time window is inappropriate to take care that the starting time difference between two operations do not differ more than a given threshold value. An explicit time window is too restrictive since we do not need the position restricting property.

In order to overcome this shortcoming and with the goal to relax the position restricting property of an explicit time window two related time window concepts are proposed. These concepts will be introduced and compared now.

2.3.2 Alternative Time Windows

de Jong et al. (1996), Favaretto et al. (2007) as well as Breier (2015) propose to define several time windows for each operation (customer site) and to give these time windows to the dispatcher of the fleet. A dispatcher has to select one of the proposed explicit time windows and all associated operation starting times must fall into the selected explicit time window. The main motivation of specifying several time windows for one customer site is to give the fleet planner more freedom to compile profitable vehicle routes. If the same time window must be selected for both operations associated with an order then the maximal allowed operation starting time difference condition is fulfilled. Alternative time windows enable the dispatcher to exploit the difference restricting property of explicitly formulated time windows. The position restricting property of an explicit time window, which is not requested here, is (partly) deactivated.

However, beside the determination of the operation starting times of the considered operations it is necessary for a fleet planner to select the appropriate time window from the set of available time windows. This is a quite complicated task since a decision problem of enlarged complexity has to be solved (de Jong et al., 1996). Two different kinds of interrelated decisions (routing as well as time window selection) must be made during the fleet dispatching process.

2.3.3 Implicit Time Windows

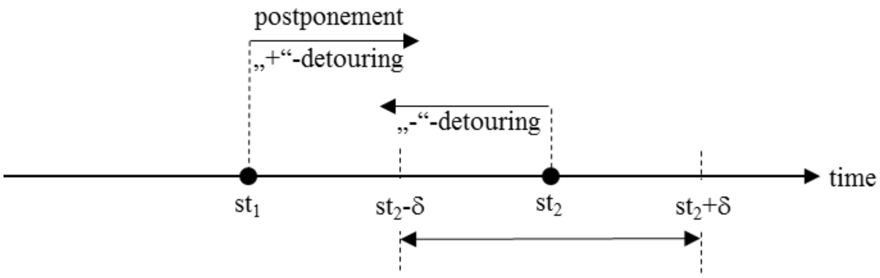
Schönberger (2015) proposes a non-stationary (or shiftable) time window approach to coordinate the operation starting times of several coupled operations. Here, it is not necessary to specify an explicit time window as part of the problem data. Instead, the maximal arrival time difference between pairs of operation starting times to be respected is added as problem data to the dispatching problem formulated directly as a constraint to be respected.

Practically, the determination of a first operation starting time at the corresponding customer location defines an explicit time window in which the second operation starting time must be determined in a feasible way. This time window reduces whenever additional operation starting times at this customer location are defined. Clausen (2011) as well as Stieber et al. (2015) introduce the term *implicit time window* for such a variable time window. Here, it is not necessary to select a time window. Only operation starting times have to be decided.

Implicit time windows provide the here required difference restricting property but not the here redundant and too restrictive position restricting property of an explicit time window. However, since the position of the implicit time window is not part of the fixed problem data it is necessary to determine this position during the solving of the fleet dispatching decision task. Therefore, implicit time windows increase the already quite high complexity of the fleet dispatching task by adding a further decision problem component.

2.4 Dispatching Strategies to Meet Implicit Time Windows

Figure 1: Options to achieve implicit time window feasibility



The common agreement of an implicit time window between a carrier and a customer, e.g. the specification of a maximal allowed time difference between two visits at the customer's location is assumed. Now, it is necessary to ensure that the agreed time window is considered during the composition of the vehicle routes.

Route composition comprises the solving of two interdependent decision tasks (the vehicle routing problem). First, it is necessary to partition the available set of od-requests into clusters (tours) and to assign each cluster to a vehicle that is able to serve the contained od-requests. Second, the loading and unloading operations associated with the od-requests in a cluster must be arranged in a sequence in order to build the executable vehicle routes (routing). Obviously, both decisions (clustering and routing) are interdependent. The need to keep the total travel distances resulting from the route execution as low as possible, makes the vehicle routing problem quite challenging and requires regularly an iterative revision of the tentatively made clustering and the tentatively made routing decisions.

Beside clustering and sequencing loading and unloading operations of the vehicles it is necessary to determine the starting time of each individual operation (schedule building). The typical scheduling approach in the context of vehicle routing is left-to-right shifting, where each operation is scheduled to start as early as possible. Here, a vehicle starts from a depot at time 0 and the arrival time of the vehicle at the first visited operation site is set by adding the travel time between the depot and this site. In case that a vehicle arrives before a given explicit time window has opened, a waiting time is inserted. The operation starting time is shifted to a later time until the earliest allowed operation time is reached. Adding the operation duration (service time) to the operation starting time determines the operation finishing time which is equal to the vehicle leaving time from the associated site. Operation starting times of subsequently visited sites are consecutively determined in the same way.

In case that the schedules for the vehicle routes are setup independently for each individual vehicle it may happen that the two determined starting times st_1 as well as st_2 ($st_1 < st_2$) of the two unloading operations associated with an order fail to fulfill the implicit time window. Such a situation is given in Figure 1. It is necessary to revise the so far made scheduling and or routing decisions. Two general revising options are available. One approach is to shift the secondly scheduled earlier operation starting time st_1 to the right until it falls in the interval $[st_2-\delta;st_2+\delta]$. This right shifting means to postpone the starting time of st_1. Postponing this operation establishes feasibility with respect to the implicit time window associated with this order. However, the right shifting of an operation requires the right shifting of all subsequently visited operations in this route so that the updated starting times are endangered to cause (additional) infeasibilities with respect to (implicit or explicit) time windows to be considered. In addition the latter scheduled operation cannot be postponed with the goal to establish implicit time window feasibility.

Another approach to vary the scheduled operation starting times st_1 or st_2 is to modify the sequence in which earlier visited operations in the two considered routes are processed. This route modification leads, in general, to additional travel distances for processing the updated route(s) (detouring). However, detouring can be applied to both unloading operations of the considered order. Modifying the sequence before operation 1 means to shift st_1 to the right („+“-detouring) but modifying the sequence of the operations before operation 2 by re-position some earlier processes operations in the route that serves operation 2 after operation 2 realizes a left shifting of st_2 („-“-detouring). Similar to postponing a request the application of detouring can lead to time window infeasibilities of other operations served by the affected route.

Taking care of the fulfillment of implicit time windows is therefore a very challenging task especially since scheduling decisions and, in several situations, routing decisions in two (or more different routes) have to be coordinated. In contrast, feasibility with respect to an explicit time window can be achieved by updating routes independently, since the explicit time window does not rely on any scheduling decision made before (for another vehicle). The position restricting property of an explicit time window takes care that after the independent shifting of st_1 and st_2 these two times still fulfill the time difference restricting property.

3. Fleet Disposition with Implicit Time Windows

Ensuring feasibility of an implicit time window associated with a customer location requires the coordination of operation starting times within two different vehicle routes. This involves the confirmation and/or revision of scheduling and/or routing decisions in at least two different routes. Scheduling concepts developed for vehicle routing problems with explicit time windows are insufficient to cope with this challenge (Solomon, 1987). They are able to compare a variable operation starting time with a fixed time window opening (or closing) time but they cannot take care about ensuring that the two starting times of operations in two different routes differ by at most δ time units. It is therefore necessary to equip such an approach with additional capabilities to take care about implicit time windows. This section contains the presentation of such an enriched combined routing and scheduling fleet management tool. In Subsection 3.1 the framework of such a combined dispatching system is presented. Subsection 3.2 contains the description of the mechanism to control the consideration of implicit time windows.

3.1 Metaheuristic Route Construction

The simultaneous route generation and schedule determination in a situation of a vehicle routing problem with implicit time windows is a very complicated and complex decision task. In Schönberger (2015) a mixed-integer linear optimization model for the situation outlined in Subsection 2.2 has been developed. It has been demonstrated that the application of a commercial model solver like IBM CPLEX is possible only for very small problem instances (with 6 orders and 12 requests). The application of a heuristic model processing algorithm seems appropriate and promising. In the remainder of this section, the development of a genetic algorithm based heuristic for searching and determining high quality solutions of the considered vehicle routing problem with implicit time windows is addressed. This genetic algorithm is an extension of the framework developed and evaluated in Schönberger (2011).

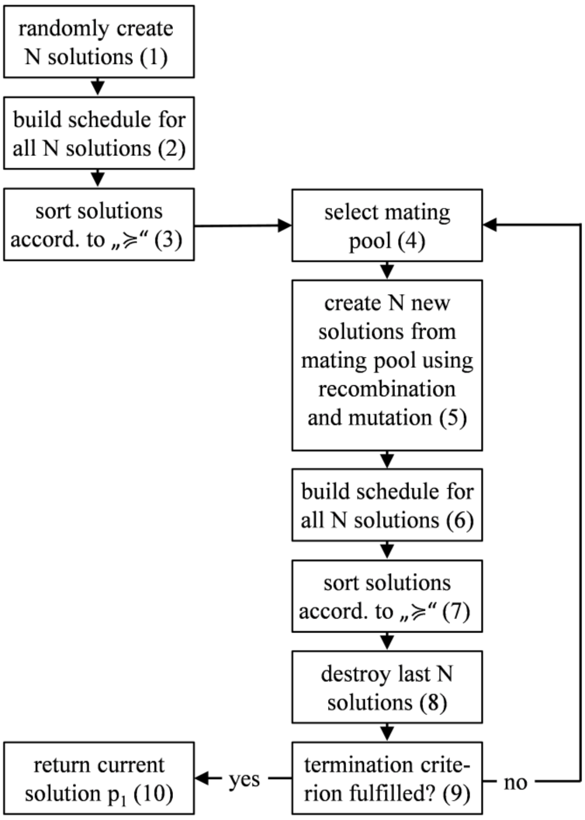
A genetic algorithm is a population-based heuristic. Here, a solution is a route set generated for the considered vehicle routing problem with implicit time windows. Given a set of N solutions (forming the „parental population“) it generates N additional solutions (forming the „offspring population“) using the three mechanisms of „selection“, „recombination“ as well as „mutation“.

Each solution in a population is evaluated and the fitness value represents a quantification of the evaluation result. We use a three-facetted evaluation scheme. The evaluation of a solution p starts with some preparatory steps. Initially, the MS^{max}-exceeding (expressed in time units) is collected from all routes (“sum of exceeding of MS^{max}”). Next, the exceeding of δ is collected from all orders (“sum of exceeding of the implicit time windows”). Using these two sums as well as the sum of travel distances associated with the routes stored in p enables a three-dimensional evaluation of the solution p. First, $F^1(p)$ gives the sum of exceeding of MS^{max} observed in solution p. Second, $F^2(p)$ carries the sum of exceeding of the implicit time windows observed in p. Finally, $F^3(p)$ represents the travel distances resulting from the route in p. Based on these three evaluation criterions, we are able to define a sorting scheme to order the members of the population („ranking“). We write „$p_1 \succcurlyeq p_2$“ (solution p_1 is ranked higher than solution p_2) according to the following definition of „$\succcurlyeq$“:

$$p_1 \succcurlyeq p_2 \Leftrightarrow \begin{cases} F_1(p_2) \geq F_1(p_1) & \\ F_2(p_2) \geq F_2(p_1) & if\ F_1(p_2) = F_1(p_1) \\ F_3(p_2) \geq F_3(p_1) & if\ F_2(p_2) = F_2(p_1) \wedge F_1(p_2) = F_1(p_1) \end{cases}$$

We can use „$\succcurlyeq$“ to sort the entire population, so that the highest positioned solutions comply with the restrictions and objectives to a higher extend then those solutions positioned at the end of the implied ranking.

Figure 2: Flow chart of the genetic algorithm fleet dispatching tool



The basic idea of a genetic algorithm based optimization procedure is to replace an existing parental population of solutions by a child population so that the average fitness observed in the child population is larger than the average fitness observed for the parental population. The replacement process is as follows. First, „selection“ selects preferentially some individuals that are positioned at the beginning of the sorted solution list according to „≽“. These selected individuals form the so-called „mating-pool“. Next, N new solutions are generated in two steps. First „recombination“ randomly selects two solutions from the mating pool and re-combines properties from both parental solutions to create a new offspring solution. After the offspring solution has been created „mutation“ implements some random variations of the offspring. After N offspring solutions have been created they are inserted into the parental population. The resulting population consists of 2·N solutions. It is sorted using „≽“. Only the solutions in the first N positions are kept and the remaining N solutions are destroyed. Now, an iteration is completed and a new iteration is initiated if a given termination criterion is not yet fulfilled (e.g. maximal number of iterations reached). Otherwise, the procedure stops.

The genetic algorithm procedure used to find and to improve feasible solutions for the aforementioned fleet management problem with implicit time windows is represented in Fig. 2. The dispatching procedure starts with the creation of randomly generated route sets (1). Next, operation starting times are determined (2). Now, all members of the population are sorted according to „$\succcurlyeq$“ (3). The initial population is iteratively replaced by another population by the genetic algorithm steps (4)-(8). First, the mating pool is selected (4). Second, offspring solutions are created (5). Operation starting times are fixed (6) followed by the determination of the ranking of solutions (7). The worse half of the mixed parental and child population is destroyed (8). After these five steps it is checked whether an a priori defined termination criterion is reached (9). If the genetic algorithm has been stopped the currently best ranked solution is returned as solution of the fleet dispatching problem (10).

3.2 Achieving Implicit Time Window Feasibility

Sets of vehicle routes are generated and evaluated during the execution of the genetic algorithm. After having ensured that the maximal makespan constraints is fulfilled, the genetic algorithm primarily searches for solutions that fulfill all implicit time windows using both options detouring as well as operation starting time postponement.

The sorting of the members of a population prefers those solution with few or even no violations of implicit time windows. In case that a solution exhibits violations of implicit time windows it is ranked quite low compared to a solution without any time window violation even if the feasible solution requires to travel longer (detours).

Usually, the scheduling procedure used in steps (2) and (6) tries to determine the earliest starting time for an unloading operation at a customer site. However, postponing the starting time of an operation can help to fulfill the implicit time window at a customer site in case that the earliest possible starting time st_1 of the currently considered operation is more than δ time units earlier than the starting time st_2 of the second operation associated with this customer site. If the starting time of the currently considered operation 1 is postponed from st_1 until st_2-δ then the maximal allowed time difference of the two operation starting times at this customer site is respected. This postponement option is implemented in the procedure responsible for the schedule determination in steps (2) as well as (6). Whenever it has to determine the starting time st_1 of a delivery / unloading operation it checks first whether starting time st_2 of the corresponding unloading operation associated with the second request in the same order has already been determined. If this is true then the earliest possible starting time is postponed as long as this postponement prevents an infeasibility with respect to the implicit time window. If the associated second operation has not yet been scheduled then the earliest possible operation starting time is assigned to the currently considered operation. If necessary, postponement is applied later to the so far unscheduled delivery operation of the currently considered order.

The schedule determining procedure employs a route-based schedule building strategy. It determines the starting times of all operations for a first route. Then it determines the starting times for all operations belonging to a second route and so on. With the goal to exploit as much postponement opportunities as possible, we sort the routes by decreasing route duration before we start we the determination of the schedules for the individual vehicles, i.e. operations in the longest lasting route are scheduled prior to operations of shorter routes.

4. Computational Experiments

This section reports about the specification, preparation, execution and evaluation of computational experiments in which the aforementioned dispatching system is assessed. The achieved results enable an estimation of additional costs as well as of other impacts of considering implicit time windows in vehicle route construction.

Subsection 4.1 addresses the specification of simulation scenarios. In Subsection 4.2 we summarize the experimental setup, i.e. we outline the conducted experiments and introduce the observed performance indicators. The presentation of the observed results as well as their analysis are found in Subsection 4.3.

4.1 Specification of Test Scenarios

In order to conduct the announced computational simulation experiments we setup a collection of test scenarios. The subsequently outlined general setup applies for all these test cases and comprises at fleet of 10 vehicles. This fleet comprises five type-A vehicles and five type-B vehicles. The fleet operates in the area represented by the square [-300; 300] × [-300; 300]. Initially, all vehicles are positioned at the trucking company’s depot at point (0;0). It is necessary that each vehicle finally returns to this location after it has completed all assigned operations.

There are two warehouses available. Each warehouse stores one commodity exclusively. Commodity A is stocked at warehouse WH-A which is located at (−150; 150). Commodity B is stocked at warehouse WH-B located at (200;−50).

There are 25 orders. Each order comprises two origin-to-destination requests (od-requests). Each od-request requires the pickup of a commodity quantity at the corresponding warehouse and the delivery of this commodity to an individual customer site. The two od-requests contained in an order fulfill the following two properties. First, their delivery locations coincide. Second, the first od-request requires the delivery of a type-A commodity but the second od-request is associated with a type-B commodity. Consequently, each of the 25 customer sites must be visited twice: once by a type-A vehicle and once by a type-B vehicle. We randomly draw five different sets of 25 customer locations using five different random number generator seeding values $\omega \in \Omega=\{1,\ldots,5\}$.

The fleet dispatcher has to setup a set of routes with a least possible sum of total travelled distance units for the fleet so that all 50 od-requests contained in the 25 orders are served. We are going to analyze the impacts of varying the maximal allowed difference δ between the two visits to be scheduled by the fleet dispatcher at each customer site (common length of the implicit time window for all customer sites). Three different situations are distinguished. If $\delta=\infty$ then there is no coordination of the two visits necessary. Preliminary experiments have revealed that arrival time difference larger than 500 time units are to be implemented if the travel distance sum over all vehicle routes is minimal. In a second experiment we therefore limit the maximal allowed unloading starting time difference at each customer site to $\delta=500$ time units. This enforces the fleet dispatcher to revise the least distance route set in order to fulfill the requirements of the implicit time windows of length $\delta=500$ time units at each customer site. Finally, in a third experiment, we want to analyze the impacts of enforcing the two unloading operations to the same starting time ($\delta=0$). In total, we analyze the three implicit time window lengths $\delta\in\Delta:=\{\infty;500;0\}$.

With the intention to keep the total travel distances as short as possible a fleet dispatcher would preferentially apply a waiting strategy to achieve the implicit time window feasibility of the generated vehicle operation schedules. The insertion of waiting times at customer sites contributes to the prolongation of the makespan, which is the time span between the leaving of the first vehicle from the depot and the return of the last vehicle to the depot. The specification of a maximal allowed makespan MS^{max} implies that the fleet dispatcher has to revise some routes in order to avoid any exceeding of MS^{max}. In the aforementioned preliminary experiments we have seen that the maximal makespan without any time-related operation starting restriction is larger than 3000 time units. The reduction of MS^{max} from (the referential value) of ∞ time units to 3000 time units makes a route set revision become necessary in order to comply with this the maximal allowed makespan. We investigate scenarios with the maximal allowed makespan values $MS^{max}\in\Pi:=\{\infty;3000;2000\}$.

In summary, following the aforementioned ideas, we setup $|\Omega|\cdot|\Delta|\cdot|\Pi| = 5\cdot3\cdot3 = 45$ different fleet dispatching (vehicle routing) scenarios. For each of the 5 customer location sets we can have 9 different time-oriented limitation sets by combining different maximal makespan values with different values for the length of the implicit time windows at the customer sites.

4.2 Setup of Experiments

In each individual simulation experiment, the genetic algorithm outlined in Section 3 is used to mimic a dispatcher that determines a feasible schedule with least travel distances for a given test case ($\omega;\delta;MS^{max}$). The genetic algorithm is a randomized procedure so that it is necessary to apply it with several random number seeding values to the same instance in order to get a reliable average solution quality estimation. Here, each of the 45 test cases is solved by the genetic algorithm with five different seeding values. This leads to $5\cdot45=225$ individual simulation experiments.

In all experiments, we observe several performance indicator values, store them and calculate the average values for each combination $(\delta;MS^{max})$ of the length δ of the implicit time window and the maximal allowed makespan MS^{max}. The averagely observed travel distance is stored in $D(\delta;MS^{max})$. Since we are interested in getting insights into the impacts of varying the length of the implicit time window, we calculate and store the relative increase $D^{var}(\delta;MS^{max}):= D(\delta;MS^{max})/ D(\infty;MS^{max})$ of the travel distance that results from the reduction of δ. Similarly, we store the average number of deployed vehicles in $V(\delta;MS^{max})$ and its relative variation in $V^{var}(\delta;MS^{max})$. Furthermore, we save the average contribution of waiting (idle) times to the total "away from the depot"-time of the deployed vehicles and store this percentage in $W(\delta;MS^{max})$.

In order to identify structural changes of a route set implied by the reduction of the implicit time window length it is necessary to compare routing as well as clustering decisions with and without consideration of the implicit time windows at customer sites. We can quantify the percentage of revised decisions using the H^2-route set comparison measure proposed in Schönberger (2015a). Let $K^{clust}(\delta;MS^{max})$ denote the percentage of revised clustering decisions (varied assignments of requests among vehicles) resulting from sharpening the length of the implicit time window from ∞ to δ. In the same way, we define $K^{seq}(\delta;MS^{max})$ to represent the percentage of the implied sequencing decision variations.

4.3 Presentation and Discussion of Results

Figure 3 shows the solution of an example instance with unlimited makespan and an implicit time window of length $\delta=\infty$ generated by the genetic algorithm. Two vehicles are deployed, one vehicle is of type A but the other one vehicle is of type B. The type B – vehicle (route printed in gray) follows the route depot→ WH-B→ X→ W→ V→ U→ T→ S→ P→ Q→ R→ Y→ F→ E→ D→ A→ G→ H→ I→ J→ K→ L→ M→ N→ O→ B→ C→ depot. The type A – vehicle (route printed in black) travels along the route depot→ WH-A→ A→ B→ C→ D→ E→ F→ G→ H→ I→ J→ K→ L→ M→ N→ O→ P→ Q→ R→ S→ T→ U→ V→ W→ X→ Y→ depot.

Figure 3: Routes generated for an instance with unlimited makespan and implicit time window length δ=∞

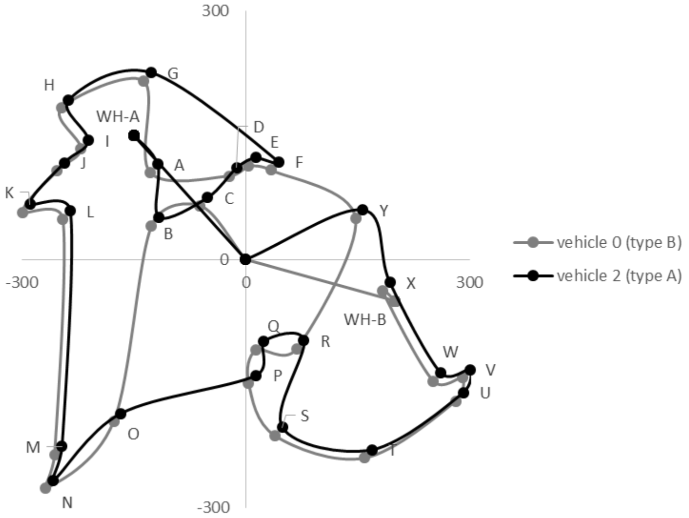


Figure 4: Routes generated for the instance from Figure 3 with unlimited makespan and implicit time window length δ=500

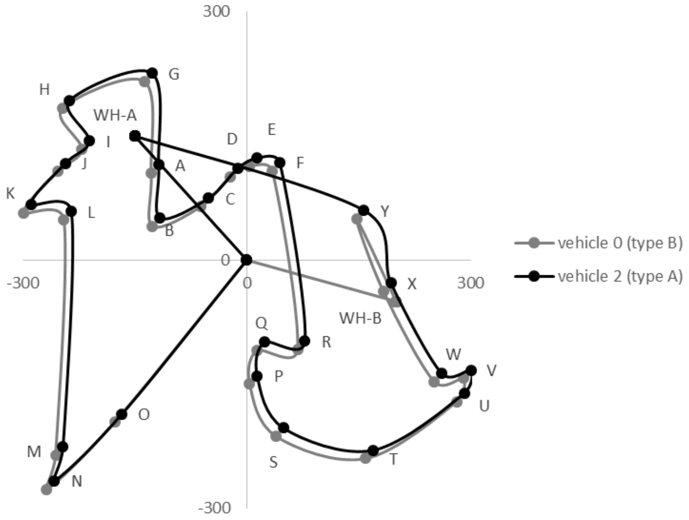


Table 1: Observed travel distances $D(\delta;MS^{max})$ and implied travel distance increase $D^{var}(\delta;MS^{max})$

δ	MS^{max}		
	∞	3000	2000
∞	5696 (0%)	6317 (0%)	6565 (0%)
500	5875 (3%)	6597 (4%)	7183 (9%)
0	5940 (4%)	7370 (17%)	8269 (26%)

Table 1 summarizes the averagely observed travel distance sum as well as the relative increase if the implicit time window length δ is reduced. In the situation that the maximal makespan of a route is not restricted ($MS^{max}=\infty$) we observe only a slight travel distance increase of 4% at most. Here, the insertion of waiting times often remedies implicit time window constraint violations. However, the insertion of waiting times does not fix the violation of an implicit time window constraint in every case. In case that a pair of customer locations is visited in two different sequences in the two associated vehicle routes, then the insertion of waiting periods does not solve the implicit time window infeasibility. For example, consider the customer locations B and W in Figure 3. In the route of the type-A-vehicle B is visited before W but in the route of the type-B-vehicle W is visited earlier than B. In addition, the time difference between the two visits at B is larger than $\delta=500$ time units. Letting the type-A vehicle wait at B would solve the conflict associated with the implicit time windows appended to B but the time window conflict at W cannot be solved. There, the arrival time difference is enlarged. To solve both conflicts it is necessary to modify the visiting sequences in at least one of the routes. This causes detours. Figure 4 shows the corresponding solution proposed for the case that $\delta=500$. The route of the type-B-vehicle is adjusted. Both vehicles follow the same visiting sequence now. Due to the need to travel first to the corresponding warehouse, the arrival times of the vehicles at the first visited customer location are different and, sometimes, the earlier arrived vehicle has to wait until the implicit time window opens to met the implicit time window requirement.

In case that the maximal allowed makespan is rather tight, then the opportunity to insert waiting times to achieve feasibility with respect to the implicit time window decreases. Now, excessive re-routing and even the incorporation of (an) additional vehicle(s) might become necessary (Figure 5 and Figure 6). Both the deviation from the shortest possible routes as well as the incorporation of additional vehicles result in additional travel distances. As it can be seen in Table 1 the total needed travel distance increases by 17% (for $MS^{max}=3000$) resp. by 26% (for $MS^{max}=2000$).

In summary, the consideration of implicit time windows leads to additional travel distances compared to the situation without time windows. Even in the situation without effective maximal makespan, small travel distance increases are observed in order to meet the requirements of an implicit time window since inserted waiting periods are insufficient to achieve time window feasibility. If the maximal allowed makespan is rather short then more than 25% of additional travel distances must be realized in order to fulfill the implicit time windows.

Figure 5: Routes generated for an instance with maximal allowed makespan $MS^{max}=2000$ and unlimited implicit time window length $\delta=\infty$

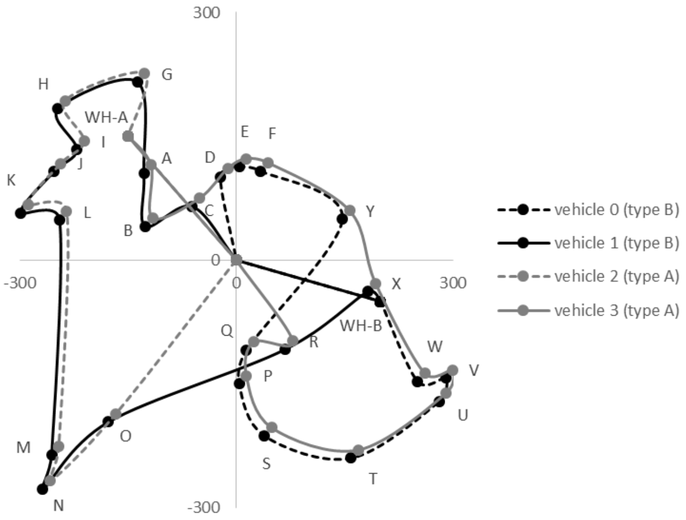


Table 2: Averagely observed number of deployed vehicles $V(\delta;MS^{max})$ and implied increase of needed vehicles $V^{var}(\delta;MS^{max})$

δ	MS^{max}		
	∞	3000	2000
∞	2 (0%)	3.52 (0%)	4.16 (0%)
500	2 (0%)	3.68 (5%)	4.64 (12%)
0	2 (0%)	3.92 (11%)	5.8 (39%)

A major driver of the additional travel distances is the increase of the number of additionally needed vehicles to be deployed in order to meet the requirements of the implicit time windows at the customer sites. Whenever a vehicle is deployed then additional travel distances for travelling back from the last customer occur. The values summarized in Table 2 show that the number of deployed vehicles can be kept stable only if the maximal allowed makespan is large ($MS^{max}=\infty$). But as soon as the route duration is limited ($MS^{max}=3000$) then the sharpening of the time window length implies an increase of the number of averagely deployed vehicles by up to 11%. If the maximal allowed makespan is quite tight ($MS^{max}=2000$) then even an increase of 39% of the number of incorporated vehicles is reported.

Figure 6: Routes generated for an instance with maximal allowed makespan MS^{max}=2000 and unlimited implicit time window length $\delta=\infty$

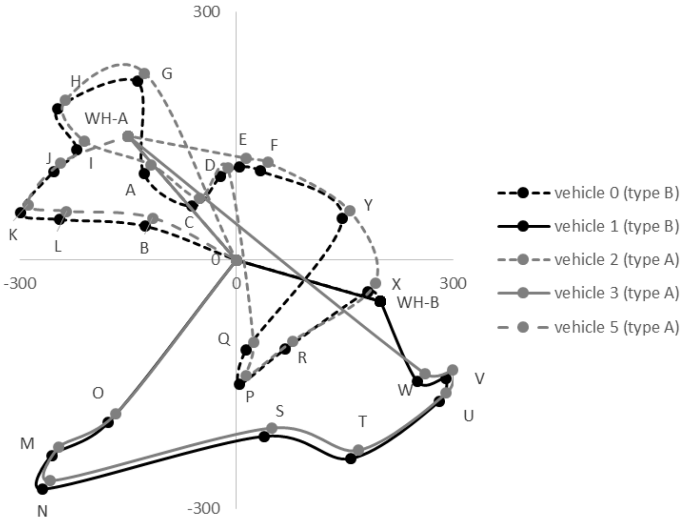


Table 3: Contribution of waiting time $W(\delta;MS^{max})$

δ	MS^{max}		
	∞	3000	2000
∞	0%	0%	0%
500	0%	12%	5%
0	3%	9%	12%

The usage of inserting waiting times to synchronize the arrival times of both vehicles at customer sites can be analyzed by means of the values compiled in Table 3. If the route duration is unlimited then the routes are quite long and waiting periods are relatively short so that these idle periods contribution to the total time until the return to the depot by 3% at most. In case that $MS^{max}=3000$ then the reduction of the length of the implicit time window down to 500 time units requires additional waiting times and the contribution of these idle times summarizes up to 12% contribution to the total operational time. A further reduction of the implicit time window length implies the deployment of additional vehicles. Now, the sum of waiting period lengths is reduced but detours (in form of additional travel distances caused by the additionally incorporated vehicles) have to be implemented to meet the implicit time window requirements. Only 9% of the total operational time is spent with waiting. In case that $MS^{max}=2000$ then the incorporation of additional vehicle does not avoid the increase of idle times. Here, up to 12% of the time vehicles are away from the depot is spent with waiting.

Table 4: Implied revision of clustering decisions $K^{clust}(\delta;MS^{max})$

δ	MS^{max}		
	∞	3000	2000
∞	0%	0%	0%
500	0%	39%	56%
0	0%	44%	59%

With the goal to get additional insights and a better understanding of the impacts of sharpened implicit time windows we compare (for a fixed maximal makespan value) the route sets proposed with and without ($\delta=\infty$) implicit time windows. In particular, we analyze the percentage of those pairs of requests that are served together in a common route without implicit time window consideration but which are not served in one route in the route set proposed for the situation with implicit time windows. Table 4 contains these percentage values. If the route duration is unlimited ($MS^{max}=\infty$) then no revision of the clustering decision is necessary to comply with the implicit time windows. In case that an effective route duration limitation is stated ($MS^{max}\leq 3000$) then more than 39% of the pairs of clustered requests are split as soon as $\delta\leq 500$. At maximum, 59% of these request pairs are split up.

Table 5: Implied revision of sequencing decisions $K^{seq}(\delta;MS^{max})$

δ	MS^{max}		
	∞	3000	2000
∞	0%	0%	0%
500	21%	48%	52%
0	21%	45%	52%

Quantifying revisions of sequencing decisions is a sophisticated task. The basic idea to determine the percentage of revised sequencing decisions is to compare again pairs of operations. However, the major challenge is that it is necessary to ensure that a pair of operations must be served by the same vehicle either in both situations for the $\delta=\infty$-situation and for $\delta=3000$ ($\delta=2000$). Otherwise, the base for a comparison would be too small to get a meaningful statement. In Schönberger (2015a) a so-called giant-route that is defined by a consecutive arrangement of the routes of all vehicles is used to overcome this challenge. This giant route contains all operations and therefore enables the comparison of the sequence among all pairs of operations. We count the percentage of pairs of operations in which both associated operations are processed in the same sequence (but not necessarily as direct successors). From the values shown in Table 5, we observe that sequencing revisions are established also in the case of an unlimited maximal route duration. Here, 21% of sequencing decisions are updated after the length of the implicit time window at the customer sites has been sharpened. Approximately 50% of the sequencing decisions are revised if the maximal allowed makespan is so small that the insertion of waiting times is not sufficient to achieve feasibility with respect to the implicit time windows.

In summary, between 10% and more than 50% of all route generating decisions (clustering as well as sequencing decisions) are revised in order to fulfill the implicit time window constraint. The incorporation of detours is necessary and causes up to 26% additional travel distances caused by the deployment of up to 39% additionally deployed vehicles.

5. Summary, Conclusions & Outlook

In this article we addressed a sophisticated extension of the well-known and broadly-investigated vehicle routing problem. The consideration of maximal allowed delivery time differences (implicit time windows) at customer sites requiring multiple visits was in the focus of the reported research. Implicit time windows are a tool to achieve time-coordination among different delivery activities at customer sites without the need to specify the absolute position of operations on the time axis as necessary when using explicit time windows. Implicit time windows enable the exploitation of more freedom during fleet disposition. However, the management of implicit time windows in computer-supported automatic fleet disposition comes along with a lot of challenges.

The contribution of this article to the understanding and promotion of implicit time windows is two folded. First, we have proposed a prototypic automatic scheduling system that is able to handle implicit time windows by inserting waiting times as well as detours to enforce coupled operation starting times in the implicit time window. Second, we have used this tool to conduct simulation experiments in which we observed the impacts of considering implicit time windows during fleet disposition. These contributions answer the research questions stated in the introduction of this research report.

The introduction and/or the sharpening of implicit time windows require the revision of routing decisions. Implicit time windows help to offer logistics service providers a better and more appropriate service level. The interface performance between (external) transport processes and (internal) downstream processes in a value chain benefits from implicit time windows. However, we have seen that a significant increase of travel distances comes along with the consideration of implicit time windows. Furthermore, more vehicles are necessary to meet implicit time window requirements in time sensitive distribution scenarios.

Although we have already achieved first insights into the benefits and drawbacks of using implicit time windows in distribution logistics further research is necessary to get a deeper understanding of this coordination tool. Especially, it is necessary to investigate setups in which implicit time windows are customized, i.e. each customer defines the length of its implicit time window individually. Second, limited vehicle as well as limited handling capacities must be integrated into the fleet disposition system. Third, other objectives guiding the vehicle scheduling process require an assessment. In this context, a total cost calculation is necessary in order to estimate the surcharge a customer has to pay for being served in a shorter implicit time window. In addition, the optimization of emissions resulting from the transport operations should be assessed in the context of implicit time windows.

6. Abstract

Enterprises as well as private households exploit multi-sourcing strategies that lead to fragmented material flows and multiple deliveries. Often, customer (unloading) sites are visited several times by different vehicles of a transport service provider. In order to avoid costly setup at business customer sites and with the goal to increase the probability to meet a private customer in a first delivery attempt it is necessary to coordinate the multiple visits. In this context moveable time windows (also called implicit time windows) are proposed as coordination tool. In contrast to explicit time windows, a moveable time window does not restrict the customer visiting time to a certain part of the time axis but it only limits the time differences among the necessary unloading operations at a certain customer site. The primary goal of the here reported research comprises the evaluation of impacts on least distance vehicle routes and on the number of required vehicles implied by the consideration of im-

plicit time windows from the perspective of a carrier company. We report about simulation experiments.

Multisourcing-Stragien von Unternehmen und Privathaushalten führen zu einer Fragmentierung von Transporten und Anlieferungsvorgängen im Wareneingang bzw. bei der Sendungsaushändigung. Häufig werden dadurch mehrfache Besuche eines Kunden durch verschiedene Fahrzeuge (eines Transportdienstleisters) notwendig. Zur Vermeidung von Umrüstaufwendungen bzw. zur Erhöhung der Wahrscheinlichkeit einer erfolgreichen Sendungsaushändigung ist eine zeitliche Abstimmung der Anlieferungen an Auslieferungsorten notwendig. In dieser Arbeit werden variable bzw. bewegliche Zeitfenster (sog. implizite Zeitfenster) als Koordinationsmechanismus vorgeschlagen und aus der Sicht eines Straßengüterverkehrsunternehmens evaluiert. Im Gegensatz zu explizit definierten Zeitfenstern wird der Belieferungszeitpunkt nicht vorab eingeschränkt sondern lediglich der Abstand zwischen den einzelnen Anlieferungen nach oben beschränkt. Das übergeordnete Ziel der hier berichteten Forschungsarbeiten umfasst die Abschätzung von Auswirkungen verschiedener Konfigurationen von impliziten Zeitfenstern. Anhand der in Simulationsexperimenten beobachteten streckenminimalen Transportprozesse werden die Auswirkungen verschiedener Konfigurationen von impliziten Zeitfenstern auf Fahrtrouten und benötigte Fahrzeuge abgeschätzt.

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