Heterogeneity of Velocity in Vehicle Routing—Insights from Initial Experiments

Jörn Schönberger and Herbert Kopfer

Abstract Vehicle routing comprises a variety of fleet disposition problems. We compare the performance of a homogeneous fleet of vehicles with the performance of a mixed (or heterogeneous) fleet of vehicles consisting of big but slow trucks and small but fast vans. We consider a scenario with operation starting time synchronization, e.g., a scenario in which two vehicles have to be assigned to a customer location and both selected vehicles must start their unloading operations at the same time. Within computational simulation experiments, we demonstrate that the fuel consumption as well as the makespan benefit from the deployment of a mixed fleet.

Keywords Vehicle routing · Heterogeneity · Velocity · Planning goals · Synchronization

Introduction and Motivation

Vehicle routing comprises a variety of fleet disposition problems (Golden et al. 2008). Planning goals targeted in vehicle routing comprise the minimization of (i) the total travel distance of the available vehicles (ii) driver working hours or (iii) fuel consumption (Kopfer et al. 2013). Time-related aspects are quite important for the determination of transport processes. Explicit time windows are considered in the determination of vehicle routes, but sometimes, a temporal coordination between the operations of two or even more vehicles commonly serving a customer demand is necessary. A vehicle routing problem with intervehicle operation time

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requirements belongs to the class of vehicle routing problems with synchronization requirements (Drexl 2012).

In this paper, we report about a project in which two vehicles commonly fulfill a customer location and must start their unloading operation at nearly the same time. At such a customer side it is required that the first arrived vehicle postpones the start of its unloading operation until the second vehicle has arrived. In order to reduce or even prevent waiting times the incorporation of quicker vehicles is reasonable. Although, these vehicles might reach customer locations earlier (and potentially contribute to the reduction of waiting times) the incorporation of such a vehicle requires the solving of two challenges. First, the payload of a quicker vehicle is reduced and, second, the margin fuel consumption for each additionally carried payload ton is also increased (Kopfer et al. 2013). In the research reported here, we want to find first answers to the following research question: *Is it useful to enrich a homogeneous fleet by a smaller but faster vehicle if the goal is to minimize makespan and waiting times in a vehicle routing problem with operation time synchronization? Is there a tradeoff between the reduced waiting times a shortened makespan and the increased margin fuel consumption (per each ton of payload)*?

A Heterogeneous Vehicle Routing Problem

Literature. Recent surveys on vehicle routing problems are delivered in the papers by Kumar and Panneerselvam (2012a, b) and the book by Golden et al. (2008). Drexl (2012) proposes a classification scheme for different types of synchronization requirements. A recent compilation of different contributions to the understanding and management of heterogeneous vehicle routing problems can be found in Subramanian et al. (2012). Lecluyse et al. (2013) investigate a scheme to consider travel times in vehicle routing problems. Time-oriented objective functions for vehicle routing problems are discussed in the context of rich vehicle routing problems (Drexl 2012a). Lahyani et al. (2011) investigates the minimization of the total waiting times in a route set as one objective function in a bi-objective-function model. The makespan minimization in vehicle routing is addressed by Rambau and Schwarz (2013).

Verbal Problem Outline. A fleet F of m vehicles is available. Each vehicle f provides payload capacity $C(f)$ and it travels with the speed $V(f)$. Vehicle f is located at a start node $S(f)$. From here, it serves some customer locations and finally travels to a terminal node $T(f)$. An individual transport demand specified by a customer is called a request. A request requires the transport of different commodities of known quantities. Here, we assume that the quantities of the different commodities are equal. Then a request $r = (r^+; r^-; q_r)$ expresses the necessity of a freight carrier to transport the quantity q_r of a commodity from the pickup location r^+ to the delivery location r^-. All known requests are collected in the request portfolio P. This portfolio is partitioned into the two sets P^{flex} and P^{reg}. Each request contained in the first mentioned set requires the assignment of exactly two vehicles from F. Such a request is called a *flexible request*. A flexible request comprises two commodities (each has the size q_r) that are not allowed to be consolidated within one vehicle. A regular request r comprises only of commodity of size $q_{r,}$ and it has to be fulfilled by one vehicle. In contrast to a split delivery vehicle routing problem (Archetti and Speranza 2013), the assignment of two vehicles to a flexible request in the here reported situation is mandatory but not an option. We first construct a directed and double-weighted mathematical graph $G = (N, A, d, s)$ from the available data as the groundwork for the definition and modeling of the investigated decision problem. Without loss of generality, we assume that all involved locations are pairwise different. Let N^+ be the set of all pickup locations r^+ ($r \in P$), and N^- is defined as the set of all delivery locations, respectively. The set $N^{cust} = N^+ \cup N^-$ comprises all customer locations, but the sets N^{start} and N^{stop} contain the home nodes and stop nodes of the vehicles. The node set N of the graph is then defined by $N: = N^{cust} \cup N^{start} \cup N^{stop}$. Each arc $(i, j) \in A: = N \times N$ has a length $d(i, j)$. For each node $i \in N$ the least stopover time $s(i)$ is known. The value $s(i)$ corresponds to the time needed to load or to unload a commodity at node i and $s(i)$ equals 0 if i belongs either to N^{start} or to N^{stop}.

The decision task to be solved is now to determine exactly one path for each vehicle $f \in F$, so that the path of vehicle f originates from node $S(f)$ (C1) and terminates in node $T(f)$ (C2). Two vehicles must be assigned to each flexible request (C3) and one vehicle has to be assigned to a regular request (C4). For request r it is necessary that the pickup node r^+ is visited before the associated delivery node r^- (C5). It is not allowed to exceed the maximal allowed payload $C(f)$ of a vehicle f at any stage of the assigned path (C6). After the paths of the vehicles are fixed it is necessary to determine the starting times of the operations to be executed in the sequence predicted by the determined paths. For each vehicle f, the earliest possible arrival time at_{fi} at node i is calculated. Furthermore, the starting time st_{fi} of the operation to be executed at i is derived as well as the completion time $ct_{fi}: = st_{fi} + s(i)$ and the time lt_{fi} at which vehicle f leaves node i. Obviously, it is $at_{fi} \le st_{fi} \le ct_{fi} \le lt_{fi}$ in case that vehicle f visits node i. The maximal time granted to vehicle f for traveling from $S(f)$ to $T(f)$ is limited. It is not allowed that the time between leaving the start node and arriving at the terminal node exceeds T^{max} time units (C7). A flexible request must be visited by the two vehicles f and g. It is necessary to coordinate the two associated delivery operation starting times st_{fi} and st_{gi}. Here, coordination is achieved if st_{fi} and st_{gi} do not differ more than DT^{max} time units (C8). A feasible solution of the outlined decision problem fulfills all the conditions (C1)–(C8).

The postulated coordination requirement let intervehicle coordination of the operation schedules of different vehicles become inevitable. Assume that vehicle f arrives at time at_{fi} at node i which is the delivery location of a flexible request. A fleet dispatcher has two options to prevent violations of the coordination requirement (C8) if the second selected vehicle g will arrive at time $at_{gi} > at_{fi} + DT^{max}$. Option one is that the dispatcher postpones the start of the unloading operation of vehicle f at node i until time $at_{gi} - DT^{max}$. However, the insertion of waiting times along the vehicle paths could lead to the exceeding of the maximal allowed path duration T^{max} and it can contribute to the prolongation of the makespan. For option two, the dispatcher instructs vehicle f to go to another node before going to node i at the expense of detours resulting in additional travel expenses and additional fuel consumption. In order to meet the makespan constraint (C7) and the coordination requirement (C8) it is necessary to consider both options for each node that requires operation starting time coordination. We will investigate the objective functions that minimize the total travel distance (MINDIST), the fuel consumption (MINFUEL), the waiting times (MINWAIT), or the makespan (MINMS).

Decision Model. Parameters are introduced in order to describe if a certain node i is a loading node or an unloading node associated with a request r. The binary parameter $p^+(r, i)$ is set to *1* if and only if node i is the pickup node associated with request r. Similarly, the binary parameter $p^-(r, i)$ is set to *1* if and only if node i is the delivery node of request r. We are going to model the aforementioned decision situation as a mixed-integer linear program using the following decision variable families: y_{rf} (binary decision variable, equals 1 if and only if request r is assigned to vehicle f); x_{ijf} [binary decision variable, equals 1 if and only if vehicle f travels along arc (i, j)]; at_{fi} (non-negative and continuous decision variable, arrival time of vehicle f at node i); st_{fi} (non-negative and continuous decision variable, starting time of un/loading vehicle f at node i); ct_{fi} (non-negative and continuous decision variable, completion time of un/loading operation of vehicle f at node i); lt_{fi} (non-negative and continuous decision variable, time when vehicle f leads node i); ω_{fi} (non-negative and continuous decision variable, inbound load carried by vehicle f to node i); Δ_{fi} (continuous decision variable, variation of the payload of vehicle f at node I, ≥0 if i is a pickup node, ≤0 if i is a delivery node contained in the path of vehicle f); MS (non-negative and continuous decision variable, represents the makespan associated with the fulfillment of the request portfolio P by fleet F).

Two different vehicles are selected to serve a flexible request (1) but a regular request is served by exactly one vehicle (2). It is not allowed to travel to a start node (3), exactly one vehicle leaves a start node (4) and constraint (5) ensures that the path constructed for vehicle $f \in F$ originates from its start node $S(f) \in N^{start}$. Similarly, it is prohibited to leave a stop node (6), exactly one vehicle terminates its path in a stop node (7), and constraint (8) enforces the termination of the path of vehicle $f \in F$ in the dedicated destination node $T(f) \in N^{stop}$. If vehicle f visits customer node i then it also leaves this node and vice versa (9). Vehicle f visits r^+ if and only if f serves request r (10) and f visits r^- if and only if f is assigned to request r (11).

$$\sum_{f \in F} y_{rf} = 2 \, \forall r \in P^{flex} \tag{1}$$

$$\sum_{f \in F} y_{rf} = 1 \, \forall r \in P^{reg} \tag{2}$$

$$\sum_{j \in N} \sum_{f \in F} x_{jif} = 0 \, \forall i \in N^{\text{start}} \tag{3}$$

$$\sum_{j \in N^{\text{cust}}} \sum_{f \in F} x_{ijf} + \sum_{j \in N^{\text{stop}}} \sum_{f \in F} x_{ijf} = 1 \, \forall i \in N^{\text{start}} \tag{4}$$

$$\sum_{j \in N} x_{S(f)jf} = 1 \, \forall f \in F \tag{5}$$

$$\sum_{j \in N} \sum_{f \in F} x_{ijf} = 0 \, \forall i \in N^{\text{stop}} \tag{6}$$

$$\sum_{j \in N^{\text{cust}}} \sum_{f \in F} x_{jif} + \sum_{j \in N^{\text{start}}} \sum_{f \in F} x_{jif} = 1 \, \forall i \in N^{\text{stop}} \tag{7}$$

$$\sum_{j \in N} x_{jT(f)f} = 1 \, \forall f \in F \tag{8}$$

$$\sum_{j \in N} x_{jif} = \sum_{j \in N} x_{ijf} \, \forall \, f \in F, \; \forall \, i \in N^{\text{cust}} \tag{9}$$

$$\sum_{i \in N^{\text{start}} \cup N^{\text{cust}}} x_{ir^+f} = y_{rf} \forall \, r \in P, \; \forall \, f \in F \tag{10}$$

$$\sum_{j \in N^{\text{stop}} \cup N^{\text{cust}}} x_{ir^-jf} = y_{rf} \, \forall \, r \in P, \; \forall \, f \in F \tag{11}$$

$$\omega_{fS(f)} = 0 \, \forall \, f \in F \tag{12}$$

$$\Delta_{fi} = \sum_{r \in P} r^+(r,i) q_r y_{rf} - \sum_{r \in P} r^{-+}(r,i) q_r y_{rf} \, \forall \, f \in F, \; \forall \, i \in N \tag{13}$$

$$\omega_{fi} + \Delta_{fi} \leq \omega_{fj} + \left(1 - x_{ijf}\right) \cdot M \, \forall \, f \in F, \; \forall \, i,j \in N \tag{14}$$

$$\omega_{fj} \leq C(f) + \left(1 - \sum_{i \in N} x_{ijf}\right) \cdot M \, \forall \, f \in F, \; \forall i, \; j \in N \tag{15}$$

$$\omega_{fT(f)} = 0 \, \forall \, f \in F \tag{16}$$

At the beginning of the route the vehicle load is 0 (12). Constraint (13) recursively determines the load variation of vehicle f at node i. The calculated load variation Δ_{fi} is used to update the vehicle payload along the vehicle path (14). The payload of a vehicle is limited by restriction (15). Finally, constraint (16) ensures that a vehicle terminates without carrying any payload. Following the classification in Drexl (2012), the constraints (12)–(16) are resource synchronization constraints that control the usage of the vehicle capacities.

$$at_{fS(f)} = st_{fS(f)} = ct_{fS(f)} = lt_{fS(f)} = 0 \; \forall f \in F \tag{17}$$

$$at_{fi} \leq st_{fi} \; \forall f \in F, \; \forall i \in N \tag{18}$$

$$st_{fi} + s(i) = ct_{fi} \; \forall f \in F, \; \forall i \in N \tag{19}$$

$$ct_{fi} \leq lt_{fi} \; \forall f \in F, \; \forall i \in N \tag{20}$$

$$ct_{fi} + \frac{d_{ij}}{v(f)} \leq at_{fi} + \left(1 - x_{ijf}\right) \cdot M \; \forall f \in F, \; \forall i, \; j \in N \tag{21}$$

$$ct_{fr^+} \leq at_{fr^-} + (1 - y_{rf}) \cdot M \; \forall r \in P, \; \forall f \in F \tag{22}$$

The requirement to visit the pickup node earlier than the associated delivery node of a request is coded in the constraint families (17)–(22). The operation times at the start nodes are set to 0 for all vehicles (17). It is ensured that the arrival time of a vehicle at a node precedes the start time of an operation at this node (18). The completion time is calculated for each operation (19). It must be earlier than the associated leaving time (20). The operations along the path of vehicle f are calculated recursively (21), taking into account the individual vehicle speeds. Vehicle f completes its loading operation at node r^+ before the unloading operation at r^- is started (22). It is reasonable to assume that the service time $s(i)$ at node $i \in N^{cust}$ is >0 and therefore the recursive arrival time calculation prevents the installation of *short cycles* which remain unconnected either to a start node or to a stop node.

$$st_{f_1 r^-} - st_{f_2 r^-} \leq DT^{max} + \left(2 - y_{rf_1} - y_{rf_2}\right) \cdot M \; \forall r \in P, \; \forall f_1, \; f_2 \in F \tag{23}$$

$$st_{f_2 r^-} - st_{f_1 r^-} \leq DT^{max} + \left(2 - y_{rf_2} - y_{rf_1}\right) \cdot M \; \forall r \in P, \; \forall f_1, \; f_2 \in F \tag{24}$$

Let r be a flexible request and let the two vehicles f_1 as well as f_2 be assigned to r. In order to ensure that both vehicles start the execution of the unloading operation at r^- in a coordinated fashion it is necessary that the starting times of the operations at r^- of both involved vehicles are similar, e.g., they differ not more than DT^{max} time units. To code this condition in terms of linear constraints, the two constraint families (23)–(24) are setup. Again, the M-factor ensures that any of these two constraints is only activated if (and only if) request r is served by both services f_1 as well as f_2.

$$lt_{fT(f)} \leq MS \leq T^{max} \tag{25}$$

Constraint family (25) limits the makespan MS to $T^{\max}$.

$$Z^{\text{MINDIST}} = \sum_{f \in F} \sum_{i \in N} \sum_{j \in N} d(i,j) \cdot x_{ijf} \tag{26}$$

$$Z^{\text{MINFUEL}} = \sum_{f \in F} \sum_{i \in N} \sum_{j \in N} d(i,j) \cdot (a_f x_{ijf} + b_f \omega_{jf}) \tag{27}$$

$$Z^{\text{MINWAIT}} = \sum_{f \in F} at_{fT(f)} - \sum_{f \in F} \sum_{i \in N} \sum_{j \in N} \frac{d(i,j)}{v(f)} \cdot x_{ijf} - \sum_{r \in P} \sum_{f \in F} y_{rf}(s(r^+) + s(r^-)) \tag{28}$$

$$Z^{\text{MINMS}} = \text{MS} \tag{29}$$

The mixed-integer linear program (1)–(25) is a multi-commodity network flow problem enriched by additional intercommodity restrictions on the node visiting times. Each flow can be evaluated by different performance indicators whose value is subject of optimization. In the here reported research, we combine the constraint set (1)–(25) with the minimization of the overall travel distance (26), the minimization of the quantity of the consumed fuel (27) as proposed in Kopfer et al. (2013) and the minimization of the total inserted waiting times (28), and the minimization of the makespan (29).

With the goal to verify the proposed decision model we have setup the transportation scenario outlined in Fig. 1. Vehicles are positioned at the depot node 0 waiting to be deployed to serve the three requests (1; 2), (3; 6), and (4; 5). The request (3; 6) is flexible, but the two remaining requests are regular. Request (4; 5) requires the movement of a quantity of 2 tons, but the request (1; 2) demands the movement of 0.5 tons. Each vehicle serving the flexible request (1; 2) must move 0.5 tons. The unloading operations of the two vehicles at node 6 must start at the same time ($\text{DT}^{\max} = 0$).

We distinguish two configurations. In the first configuration (HOM), a homogeneous fleet comprising four identical vehicles of category $VC_{7.5}$ (Kopfer et al. 2013) is available. Each of these vehicles has a payload capacity of 3.25 tons, and the speed is scaled to 1 distance unit per time unit. The fuel consumption is determined by the parameters $a_f = 15$ and $b_f = 1.54$ for $f = 1,\ldots, 4$. In the second

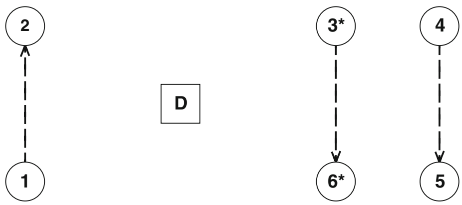

Fig. 1 Layout of the test scenario

configuration (HET), a fifth vehicle is added to the fleet. This additional vehicle belongs to the vehicle category $VC_{3.5}$. It has a payload capacity of 1.5 tons, but its speed is 1.5 distance units per time unit. Its fuel consumption is determined by $a_3 = 8$ and $b_3 = 3.31$.

Computational Experiments

We observe the four performance indicators travel distance, fuel consumption, makespan, and waiting time of a route set. In an initial experiment (first phase experiment), we optimize these four indicators individually. To do this, we combine the constraints (1)–(25) with each of the four objective functions (26)–(29) into a mixed-integer linear program. This program is configured for the two settings HET and HOM and each of the resulting 8 instances is solved using IBM CPLEX 12.4. We get the minimal objective function values $Z(\alpha, \beta)$ ($\alpha \in$ {MINDIST; MINFUEL; MINWAIT; MINMAKESPAN}, $\beta \in$ {HOM; HET}).

$$Z(\text{MINDIST}, \beta) \geq \sum_{f \in F} \sum_{i \in N} \sum_{j \in N} d(i,j) \cdot x_{ijf} \tag{30}$$

$$Z(\text{MINFUEL}, \beta) \geq \sum_{f \in F} \sum_{i \in N} \sum_{j \in N} d(i,j) \cdot (a_f x_{ijf} + b_f \omega_{jf}) \tag{31}$$

$$\begin{aligned} Z(\text{MINWAIT}, \beta) \geq & \sum_{f \in F} at_{fT(f)} \\ & - \sum_{f \in F} \sum_{i \in N} \sum_{j \in N} \frac{d(i,j)}{v(f)} \cdot x_{ijf} \\ & - \sum_{r \in P} \sum_{f \in F} y_{rf}(s(r^+) + s(r^-)) \end{aligned} \tag{32}$$

$$Z(\text{MINMAKESPAN}, \beta) \geq \text{MS} \tag{33}$$

In another experiment (second phase experiment), we repeat the previous eight experiments but we add one of the constraints (30)–(33) to the original model in order to control the corresponding performance indicator value that is not addressed in the objective function. If we use for example, the distance minimization objective function (26) then we setup and solve the following decision models consisting of the original constraint set (1)–(25) plus (a) constraint (31), (b) constraint (32), and (c) constraint (33).

Table 1 Results from computational experiments

Obj.	Ref.	Ref.	(31)	(32)	(33)
$Z^{MINDIST}$	HOM	(994.32)	1052.44 (+6 %)	1056.13 (+6 %)	1263.45 (+27 %)
	HET	(994.32)	1052.44 (+6 %)	994.32 (+6 %)	1263.45 (+27 %)
			(30)	(32)	(33)
$Z^{MINFUEL}$	HOM	(273.05)	300.58 (+10 %)	273.60 (+0 %)	304.70(+12 %)
	HET	(268.42)	295.92 (+10 %)	268.42 (+0 %)	301.23 (+12 %)
			(30)	(31)	(33)
$Z^{MINWAIT}$	HOM	(0)	128.90	320	0
	HET	(0)	24.65	166.07	0
			(30)	(31)	(32)
Z^{MINMS}	HOM	(436.23)	601.81(+40 %)	850.63 (+95 %)	436.23 (+0 %)
	HET	(436.23)	472.52 (+8 %)	696.70 (60 %)	436.23 (+0 %)

The different optimal objective function values from the HOM and HET settings are reported in the second column in Table 1. The incorporation of the faster vehicle has several benefits which are striking for the time-oriented waiting time objective function as well as for the makespan minimization if one of the other available performance indicators is limited to the least possible amount (shown in columns 4–6 in Table 1). In case that the distance is not allowed to exceed the minimal distance 994.32, then the amount of required waiting time (at node 6) is reduced significantly if the faster vehicle is considered (compared to the HOM scenario). Also the increase of the makespan as a response to the limitation of the allowed fuel consumption and the prohibition of waiting at node 6 is less if the faster vehicle is deployed (HET). The overall required fuel consumption does not increase compared to the situation that can use only the bigger vehicles.

Figure 2 shows the variation of the optimal route set in response to controlling one of the additional performance indicators in the MINMS experiments. Here, one of the constraints (30)–(32) is added to the original decision model (1)–(25), (29) in each experiment. The impacts of the utilization of the faster vehicle are striking. First, in case that the minimal travel distance is limited ((HET; MINMS) + (30)), the fastest vehicle is assigned to the longest route in order to keep the makespan as short as possible. Second, in case that it is necessary to keep the fuel consumption as low as possible then the faster vehicle is assigned to the longest route, but a long part of this route requires empty travel. In the last experiment ((HET; MINMS) + (32)), the fastest vehicle cannot be assigned to the longest route since 2 tons must be moved from 4 to 5 and the faster vehicle can carry only a payload weight of 1.5 tons.

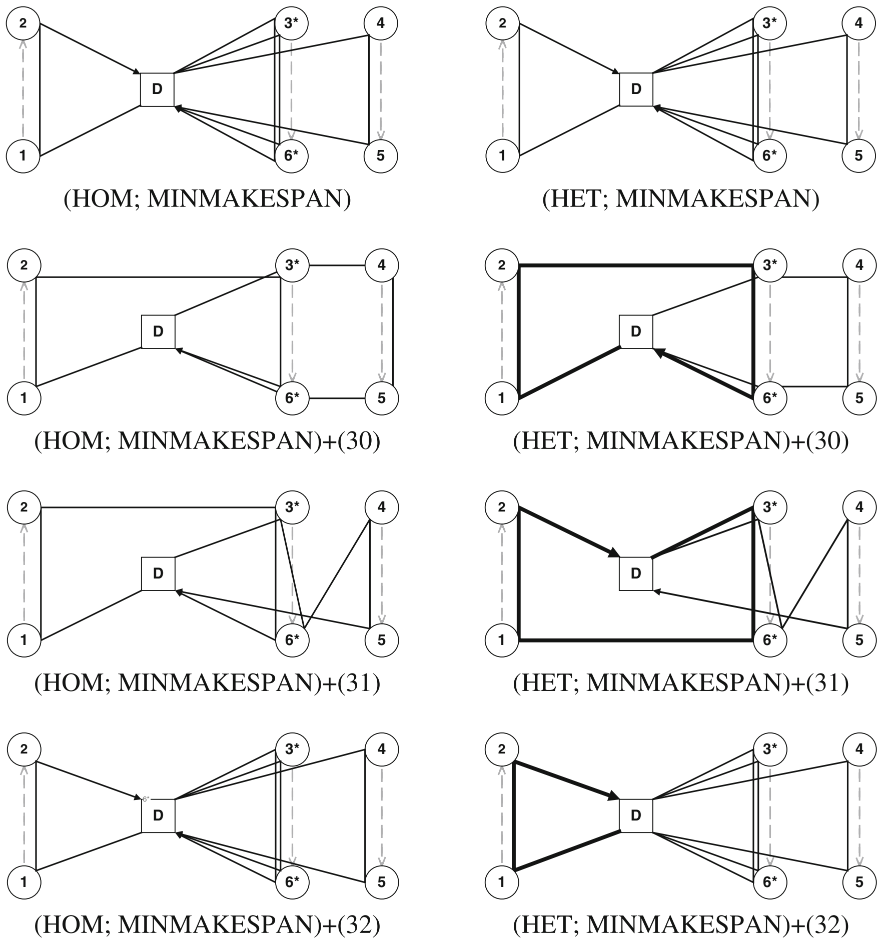

Fig. 2 Variations of the routes in case that the makespan minimization is targeted and one of the other performance indicators is under control by an additional constraint

Conclusion

We have investigated the benefits of enriching a homogeneous fleet of identical vehicles by a faster vehicle. This vehicle consumes more fuel and its payload is reduced compared to the other vehicles. However, in case that it is assigned to execute a route then it helps to reduce the consumption of fuel, and the makespan if the total travel distance is limited or if the total fuel quantity available is limited to a quite low quantity.

Future research will address more complex scenarios. The incorporation of small but fast vehicles is promising, if explicit time windows compromise the compilation of comprehensive routes. Here, we expect that the deployment of fast vehicles will lead to the reduction of the makespan and to the saving of fuel.

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