Two-echelon city logistics by integrating road and water transport: Amsterdam case study

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1 INTRODUCTION

This study investigates the efficiency of integrated water- and land-based transportation (IWLT) systems in meeting the growing transport and logistics demand in urban areas. This growth is coupled with regulations towards the much-needed sustainability considerations that limit the reach of logistics vehicles in cities. The use of inland waterways becomes interesting for service providers, and policymakers. In line with this, we explore the potential of IWLT systems in reducing costs and improving the livability of cities. The performance of an IWLT system depends heavily on the design of transshipment facilities, or satellites, where goods are transferred from the water network to the road network. Instead of investing in resources at satellites, public spaces can also be utilized as transshipment points, such as parking spots and public transportation stops. However, this requires exact synchronization between city freighters and vessels to ensure they are present at the satellites for transshipment and forces all vehicles to wait if necessary. Therefore, in this paper, we adopt a system-wide modeling for the synchronization and integration of the IWLT system. Many studies in the literature, on the other hand, assume unlimited resources at these places, ignoring the practical constraints of time, space, and labor. Furthermore, they mainly concentrate on the tactical and operational level of two-echelon routing problems, neglecting the strategic aspects of network design, such as satellite location decisions and their impact on fleet composition.

In this study, we develop a decomposition method to model and test different variants of IWLT systems. The case study considers a delivery service in Amsterdam, the Netherlands, where inland waterways cover 25% of the city's land area. The municipality of Amsterdam has prioritized innovative waterborne solutions for logistics activities, specifically for construction and hospitality sectors due to their largest logistics flows, ensuring they take place within appropriate space and time and with a minimal footprint (Gemeente Amsterdam, 2024). Based on the case study, we evaluate various design options to obtain managerial insights about the trade-offs between infrastructure investments and logistics costs as well as the impact on the livability of the urban areas. The proposed decomposition method coupled with an iterated search mechanism enables us to tackle real-size instances with around 700 customer nodes.

2 PROBLEM DESCRIPTION

The considered IWLT system is formulated as a synchronized two-echelon problem as illustrated through a simple example in Figure 1. The first echelon is the water level with vessels moving on city canals and the second echelon is the street level where light electric freight vehicles (LEFV) are operating on the road. The first echelon vehicles start from distribution centers (DC), visit

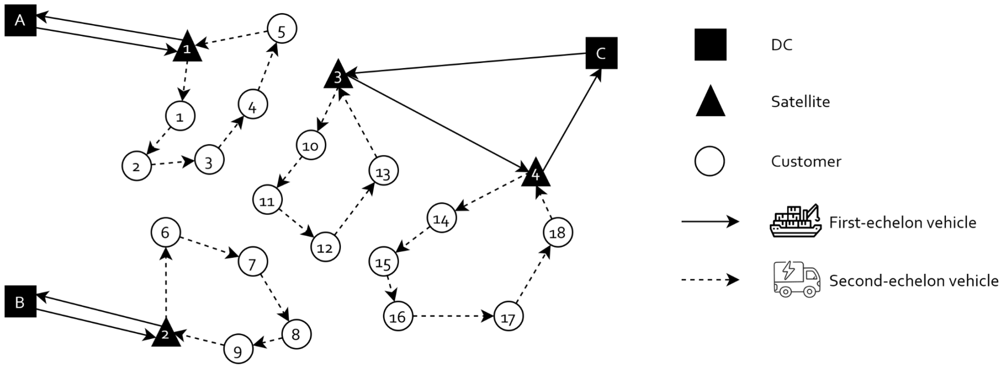

Figure 1 – *Illustration of the two-echelon IWLT system*

satellites, and come back to the DC. The second echelon vehicles then handle the delivery to the customers from the satellites. The two echelons are therefore connected through satellites that have various resource limitations representing differences in storage dedication and vehicle composition in the real world. Therefore, we consider two classes of IWLT systems:

- Asynchronous systems `(asynch)` rely on the dedicated storage capacities at the satellites. While the storage option reduces fleet costs by eliminating the temporal dependency, it brings inventory investment and management challenges.

- Synchronized systems `(synch)` rely on the efficient coordination and synchronization at the satellites. While synchronization reduces the cost of storage investments, it introduces synchronization costs for addressing spatiotemporal dependencies.

For both `(asynch)` and `(synch)` systems, the second echelon is represented by a multi-depot multi-trip VRP where the main decisions are the routing of LEFVs and the transfer decisions. The first echelon, on the other hand, has the main decision of routing the vessels based on the satellite decisions. It is represented by a capacitated VRP for the case of `(asynch)` systems and expanded with time windows for `(synch)` to ensure temporal synchronization.

3 DECOMPOSITION-BASED SOLUTION APPROACH

The routing problems in each echelon are the building blocks for the decomposition method we consider to tackle this large-scale problem. Feasible solutions are created considering compatible solutions for the involved subproblems and the overall logistics cost is improved using an iterated search mechanism which is an iterated Tabu Search (ITS).

ITS is a metaheuristic algorithm that integrates tabu search with iterated local search making use of both diversification and intensification (Cordeau & Maischberger, 2012). Due to the complexity of optimizing each street-level solution regarding the overall two-echelon setting, we employ an Adaptive Large Neighborhood Search (ALNS). ALNS uses a multi-level destroy operator that randomizes several decisions and the repair operators thereafter need to respect the T. The aim is to change the sequences of the routes to eliminate undesired routes and explore different solutions. The overall ITS solution method embedding Tabu Search, Local Search, and ALNS is provided in Algorithm 1.

R represents the set of routes on the street and T is the Tabu list consisting of routes that cannot be visited in time by a vehicle considering the transshipment decisions at the satellites. The initialization is carried out based on a greedy multi-start heuristic where street routes are constructed considering the assignment to the closest satellite and the customers are inserted based on minimum relaxed cost while respecting T. The initial solutions are improved based on Local Search with customer relocation and route segment crossover moves (Tarantilis *et al.*,

Algorithm 1 ITS($synch$, n_of_start, max_iter_{ITS}, max_iter_{LS}, max_iter_{ALNS})

```
$found\_list\_routes \leftarrow emty\_list$; $R^* \leftarrow best\_objective\_value \leftarrow inf$
$R_0 \leftarrow$ INITIALIZATION($n\_of\_start$)
$found\_list\_routes \leftarrow$ LOCAL_SEARCH($R_0, max\_rep_{LS}, max\_iter_{LS}$)
$R^* \leftarrow$ UPDATE_TABU_ LIST($found\_list\_routes, T, synch$)
$its\_iter \leftarrow 1$
while $its\_iter \leq max\_iter_{ITS}$ do
    Diversification: $SAA \leftarrow \frac{SAA}{its\_iter}$ & initial scores
    $R_{ALNS} \leftarrow$ ALNS($R^*, max\_iter_{ALNS}$)
    Intensification: $max\_iter_{LS} \leftarrow (its\_iter)(max\_iter_{LS})$
    $found\_list\_routes \leftarrow$ LOCAL_SEARCH($R_{ALNS}, max\_rep_{LS}, max\_iter_{LS}$)
    $R_{new} \leftarrow$ UPDATE_TABU_ LIST($found\_list\_routes, T, synch$)
    if $R_{new} < R^*$ then
        $R^* \leftarrow R^{new}$
    end if
end while
return $R^*$
```

2008). This Local Search is also used later in the algorithm to improve the solutions provided by ALNS.

Throughout the algorithm, T is updated based on the solutions found by the search methods. For any solution found for the street level, the multi-trip VRP is used to optimize the solutions. The ones deemed infeasible at this step are added to the T and those that are feasible are passed to the two-echelon problem to see if we obtain better feasible solutions. Therefore, at each update of T, we not only update T but also potentially the incumbent solution.

Table 1 – *Benchmark results*

		#vehicles		**travel distance**			**#transfers**
		street	**water**	**total**	**street**	**water**	
Grangier et al. (2016)	**c201**	3	2	1389.4	837.8	551.6	14.0
	c202	3	2	1305.0	848.9	456.1	15.0
	c203	3	2	1272.4	816.3	456.1	14.0
	c204	3	2	1237.7	781.6	456.1	14.0
	c205	3	2	1312.4	856.3	456.1	15.0
	c206	3	2	1312.7	856.6	456.1	14.0
	c207	3	2	1280.4	824.3	456.1	14.0
	c208	3	2	1278.5	822.4	456.1	14.0
	Avg	*3*	*2*	*1298.6*	*830.5*	*468.0*	*14.3*
					with (% differences)		
Our ITS	**c201**	3	2	1390.5 (+0.1)	838.9 (+0.1)	551.6 (-0.0)	13.0
	c202	3	2	1328.3 (+1.8)	823.2 (-3.0)	505.1 (+10.7)	13.0
	c203	3	2	1339.4 (+5.3)	834.3 (+2.2)	505.1 (+10.7)	13.0
	c204	3	2	1265.0 (+2.2)	794.3 (+1.6)	470.7 (+3.2)	13.0
	c205	3	2	1311.3 (-0.1)	806.2 (-5.9)	505.1 (+10.7)	12.0
	c206	3	2	1331.0 (+1.4)	860.3 (+0.4)	470.7 (+3.2)	13.0
	c207	3	2	1350.0 (+5.4)	893.9 (+8.4)	456.1 (-0.0)	13.0
	c208	3	2	1312.5 (+2.7)	856.4 (+4.1)	456.1 (-0.0)	14.0
	Avg	*3*	*2*	*1328.5 (+2.3)*	*838.4 (+1.0)*	*490.1 (+4.7)*	*13.0*

4 NUMERICAL RESULTS

For evaluating the proposed approach we first compare it to a benchmark from the literature as a form of validation. The performance is compared to the state-of-the-art method by Grangier

Table 2 – *Case study results*

	data		#vehicles		travel distance			runtime
	set	#satellites	street	water	total	street	water	(secs)
`asynch`	1	10	24	60	741,684	421,342	320,342	7,256
	2	10	22	57	728,955	399,421	329,534	5,703
	3	10	25	58	747,220	401,233	345,987	5,975
`synch`	1	34	21	60	768,177 (+3.6%)	411,421 (-2.4%)	356,756 (+11.4%)	9,783
	2	28	20	57	737,788 (+1.2%)	365,134 (-8.6%)	372,654 (+13.1%)	6,850
	3	25	22	58	811,107 (+8.5%)	387,543 (-3.4%)	423,564 (+22.4%)	7,446

et al. (2016), making use of Solomon instances with 100 nodes with clustered demand (c201-c208) representing a similar setting to our city logistics case. We present the results in Table 1 where our approach produces similar results to the benchmark. Nevertheless, in our formulation, we penalize the number of transfers at satellites which is not the case in the benchmark. This leads to longer distances traveled on the waterways. We kept this formulation as it is desired in our case study. The run time for our approach is on average around 32 min and for the benchmark it is reported as around 50 min for the same instances.

Then, we provide results for the case study in Amsterdam using three datasets with different demands spanning 744, 689, and 726 customer nodes, respectively. The results for these data sets with `asynch` and `synch` systems are presented in Table 2. It is seen that with synchronization we can reduce street travel significantly following the city goals even though this means the vessels will travel more on the water. Moreover, the runtime for these instances with around 700 customer nodes can be handled in a matter of a few hours thanks to the developed methodology. Note that, the number of total satellites is more for the `synch` system, but this does not mean they are all used at the same time. Further analysis of the distribution of satellite utilization will be provided.

The case study evaluation is ongoing work and we plan to present further results evaluating different design choices for such city logistics problems. Furthermore, in benchmark comparison, there are various parameters that affect the quality and runtime of our method which will be discussed with further results.

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