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Two-echelon Multi-trip Vehicle Routing Problem with Synchronization for An Integrated Water- and Land-based Transportation System

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SHORT SUMMARY

This study considers an integrated water- and land-based transportation (IWLT) system for waste collection. Research on the issue is motivated by increased heavy street movements that damage quay walls as well as congestion. We present a novel two-echelon vehicle routing problem with satellite synchronization based on a two-index formulation and evaluate it on small-sized instances for 10 waste points and 4 hubs. We compare the proposed synchronized IWLT approach with three benchmarks that can reduce issues associated with heavy loads. It is shown that the proposed system can provide better solutions with less collection cost, reduced street movements and lightweight garbage vehicles.

Keywords: City logistics; Integrated water- and land-based transportation; Multi-trip; Satellite synchronization; Two-echelon vehicle routing problem

1. INTRODUCTION

The interest towards logistics over inland waterways has been increasing recently as cities plan to reduce on-street congestion and emissions (Amsterdam.nl, 2019). Amsterdam, the Netherlands, for example, aims at further harnessing its extensive waterway network, which covers 25% of the city's central area, to improve its waste collection system. This system is based on heavy garbage trucks, which, besides worsening congestions, contribute to damaging the city's historical and fragile quay walls, resulting in billions of euros in maintenance costs (TheMayor.EU, 2021).

In order to reduce heavy vehicle movements and prevent quay wall damage, this study proposes an *integrated water- and land-based transportation* (IWLT) system that eliminates heavy garbage trucks entirely. As pointed out by Anderluh, Nolz, Hemmelmayr, and Crainic (2021), two-echelon systems may help alleviate the impact of growing freight movements on society, the economy, and the environment caused by the development of e-commerce and same-day delivery services. At the first echelon, small garbage cars collect waste. Next, at the second echelon, waste is consolidated onto larger vessels that meet the cars at the hubs. Finally, full vessels sail to a central waste facility.

We model this hybrid waste collection system as a variant of the *two-echelon capacitated vehicle routing problem* (2ECVRP) introduced by Gonzalez-Feliu (2008). Typically, 2ECVRPs aim at routing and consolidating freight through intermediate satellites connecting echelons before transferring it to a final destination (Perboli, Tadei, & Vigo, 2011). Unlike most 2ECVRP models in the literature, which consider a delivery scenario where items are first consolidated and then dispatched, we model a reverse logistics problem (see Figure 1).

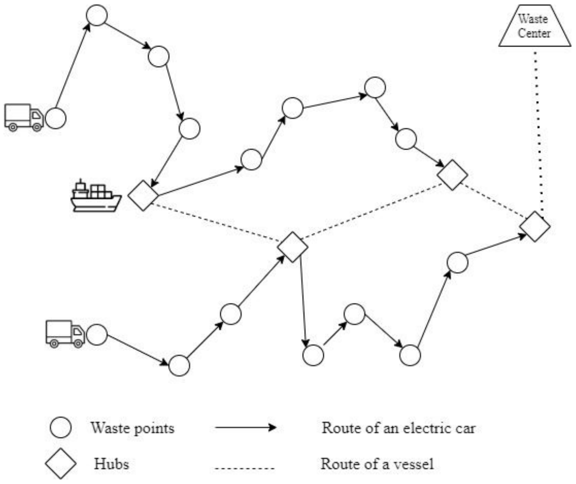

Figure 1: Two-echelon waste collection network.

The first echelon problem consists of finding routes for cars and selecting the best hubs for the transfer tasks, while the second echelon problem consists of finding routes for the vessels to serve these transfer tasks. Due to their low capacity, cars may execute multiple transfer tasks, leading to multiple trips to hubs. Therefore, vessels and cars should be in sync to be present at hubs to perform the transfer tasks. Synchronizing vessels and cars is further constrained by time windows (collection hours vary per neighborhood) and physical space (only a single vessel can access a hub at a time and perform a single transfer task at once).

Most studies have focused on the basic variant of 2ECVRP where the synchronization is required only for cargo flow (Cattaruzza, Absi, Feillet, & González-Feliu, 2017). Since satellites may lack storage capabilities or feature temporary storage capacity, temporal synchronization may also be necessary: first echelon vehicles should not arrive after the departure of second echelon vehicles (Li, Chen, Wang, & Bai, 2021). Crainic, Ricciardi, and Storchi (2009) first introduce the 2ECVRPs with time windows and temporal satellite synchronization (2E-VRPTW-SS) and propose a general model for a multi-depot multi-trip variant considering heterogeneous vehicles.

Although many studies have focused on multi-trip 2E-VRPTW-SS variants (see, e.g., Grangier, Gendreau, Lehuédé, & Rousseau, 2016; He & Li, 2019; Anderluh et al., 2021), to the best of our knowledge, none has considered vehicle transfer constraints. They assume that multiple transfer operations can occur simultaneously at a hub, which is not feasible for the Amsterdam waste collection use case where space for maneuvering cars and vessels is limited. Hence, in this study, we model a multi-trip 2E-VRPTW-SS with one-to-one transfers (2E-MVRPTW-SS). Additionally, from a practical view, we analyze different logistic systems that integrate water and land for waste collection problems in cities.

The remainder of the paper is organized as follows. Section 2 formulates the problem as a *mixed-integer linear programming problem* (MILP). Section 3 lays out an experimental study where we compare the solution quality of the proposed model with three benchmarks on modified Solomon's (1987) test instances. Finally, Section 4 is devoted to the conclusions and further directions.

2. PROBLEM FORMULATION

The 2E-MVRPTW-SS is formulated as a MILP. The first echelon is the street level, where we have K_1 identical electric cars with a capacity of Q_1 units. These cars start their journey at the main depot (d), visit a set of waste points (C), and return to the main depot without exceeding their capacity at any point. Each waste point i requires q_i units of waste to be collected within a time window of (a_i,b_i) associated with a service time of s_i. t_{ij} and c_{ij} denote the shortest travel time and travel cost between points i and j, respectively. Cars can unload the waste onto vessels at a set of transshipment hubs S over multiple trips. Transferring waste requires U time units. The second echelon is the water level where K_2 identical vessels with a capacity of Q_2 units start at the waste centre (w), visit hub(s) if cars require transfer task(s), and return to the waste centre. The x_{ij} variable determines whether a car serves point j immediately after serving point i while v_{is} decides whether the car visits hub s immediately after serving point i. x_{ij} gives the order in which waste points are assigned to a car while v_{is} provides the selected hub and the last point in a trip. The hub selection decisions by v_{is} enable us to correctly calculate the total load on the car and the earliest arrival time of a car at the hub s according to the service decisions of the last point i. If v_{is} is 1, then there is a transfer task at hub s with a demand equal to the total waste on the car after serving point i denoted by m_i and earliest service start time equal to the service end time at point i denoted by $h_i + s_i$ plus travel time to hub s. In this way, the model jointly decides the first echelon routes and transfer tasks for the second level routing problem. The second echelon sub-problem (vessel routing) is a basic VRP where a fleet of vessels serves all the transfer tasks required by the first echelon decisions respecting capacity of the vessels and the maximum time duration, operational times represented by a_w and b_w for the waste centre. The vessel routing decisions are taken by y variables. The synchronization is achieved by the earliest service start time for a transfer task at a hub and delayed arrival time to the next point, accordingly to the service end time of the transfer task plus travel time to next point. All sets, parameters and decision variables are presented in Table 1.

Table 1: Notation for the 2E-MVRPTW-SS.

Sets	
d	The depot for electric cars
w	The waste centre for vessels
C	Waste points, $\{1,\dots,n\}$
C_d	Waste points and the depot d, $C \cup \{d\}$
S	Hubs
Parameters	
t_{ij}	Shortest travel time from waste point i to j
c_{ij}	Cost of travelling from node i to j
Q_1	Capacity of an electric car
Q_2	Capacity of a vessel
K_1	The number of available electric cars
K_2	The number of available vessels
s_i	Service duration of node
q_i	Waste amount at node
a_i	Earliest collection time of node i
b_i	Latest collection time of node i
U	Constant duration for a transfer task
β_1	The fixed cost of an electric car
β_2	The fixed cost of vessel
M	Sufficiently large number for constraint linearization
Variables	
x_{ij}	(Binary) 1 if node j is visited immediately after node i, 0 otherwise
v_{ip}	(Binary) 1 if the hub p is visited immediately after node i is served, 0 otherwise
m_i	Total load on the car after node i is visited
h_i	Service start time at node i
ε_i	Extra travel cost to visit a hub after node i
$y_{ip,jr}$	(Binary) 1 if the transfer task ip is served by a vessel immediately after the transfer task jr
$y_{w,ip}$	(Binary) 1 if the transfer task ip is served as the first task by a vessel
$y_{ip,w}$	(Binary) 1 if the transfer task ip is served as the last task by a vessel
u_i	Service start time for the transfer task requested immediately after visiting node i
l_i	Total load on the vessel at the departure from the transfer task requested immediately after visiting i

$$\min\Big(\sum_{i\in C}\beta_1 x_{di}+\sum_{i\in C}\sum_{p\in S}\beta_2 y_{w,ip}\Big)+\Big(\sum_{i,j\in C_d}c_{ij}x_{ij}+\sum_{i\in C}\varepsilon_i\Big)+\Big(\sum_{i,j\in C}\sum_{r,p\in S}c_{pr}y_{ipjr}+\sum_{i\in C}\sum_{p\in S}c_{wp}y_{w,ip}+c_{pw}y_{ip,w}\Big) \tag{1}$$

subject to

$$\sum_{j\in C_d} x_{ij}=1 \qquad i\in C \tag{2}$$

$$\sum_{j\in C_d} x_{ji}=1 \qquad i\in C \tag{3}$$

$$\sum_{i\in C} x_{di}=\sum_{i\in C} x_{id}\le K_1 \tag{4}$$

$$\sum_{p\in S} v_{ip}\ge x_{id} \qquad i\in C \tag{5}$$

$$\varepsilon_i\ge (c_{ip}+c_{pj}-c_{ij})(x_{ij}+v_{ip}-1) \qquad i\in C, j\in C_d, i\neq j, p\in S \tag{6}$$

$$m_j-m_i\ge q_j-Q_1(1-x_{ij}+\sum_{p\in S}v_{ip}) \qquad i,j\in C, i\neq j \tag{7}$$

$$a_i\le h_i\le b_i \qquad i\in C \tag{8}$$

$$a_d+t_{dj}\le h_j \qquad j\in C \tag{9}$$

$$h_i+s_i+t_{ij}\le h_j+M(1-x_{ij}) \qquad i\in C, j\in C_d, i\neq j \tag{10}$$

$$u_i+(U+t_{pj})v_{ip}\le h_j+M(1-x_{ij}) \qquad i\in C, j\in C_d, i\neq j, p\in S \tag{11}$$

$$u_i\ge h_i+s_i+t_{ip}v_{ip} \qquad i\in C, p\in S \tag{12}$$

$$\sum_{p\in S} v_{ip}\le 1 \qquad i\in C \tag{13}$$

$$y_{w,ip}+\sum_{j\in C}\sum_{r\in S} y_{jr,ip}=v_{ip} \qquad i\in C, p\in S \tag{14}$$

$$\sum_{j\in C}\sum_{r\in S} y_{ip,jr}+y_{ip,w}=v_{ip} \qquad i\in , p\in S \tag{15}$$

$$\sum_{i\in C}\sum_{p\in S} y_{w,ip}=\sum_{i\in C}\sum_{p\in S} y_{ip,w}\le K_2 \tag{16}$$

$$l_i\ge m_i \qquad i\in C \tag{17}$$

$$l_j-l_i\ge m_j-Q_2(1-\sum_{p\in S}\sum_{r\in S} y_{ip,jr}) \qquad i,j\in C, i\neq j \tag{18}$$

$$a_w+t_{wp}v_{ip}\le u_i \qquad i\in C, p\in S \tag{19}$$

$$u_i+U+t_{pr}\le u_j+M(1-y_{ip,jr}) \qquad i,j\in C, p,r\in S, i\neq j \tag{20}$$

$$u_i+U+t_{pw}v_{ip}\le b_w \qquad i\in C, p\in S \tag{21}$$

$$x_{ij}\in\{0,1\} \qquad i,j\in C_d, i\neq j \tag{22}$$

$$v_{ip},\ y_{w,ip},\ y_{ip,w}\in\{0,1\} \qquad i\in C, p\in S \tag{23}$$

$$y_{ip,jr}\in\{0,1\} \qquad i,j\in C, i\neq j, p,r\in S \tag{24}$$

$$m_i\ge q_i \qquad i\in C \tag{25}$$

$$\varepsilon_i\ge 0 \qquad i\in C \tag{26}$$

Objective function (1) minimizes the total number of used vehicles (vessels or cars) and the transportation costs for cars and vessels. The first part is the number of total vehicles, the second is the transportation cost for street level and the last part is the transportation cost for water level. Constraints (2) and (3) ensure that each waste point is served exactly once by a car while constraints (4) indicate that the number of leaving and returning cars must be equal and should not exceed available fleet size. Constraints (5) guarantee that a car must visit a hub before returning to the depot in order to transfer the collected waste in its last trip. Constraints (6) calculate the additional travel cost to visit a hub s between points i and j, assuming triangle inequality holds for all i, j pairs. Constraints (7) are capacity constraints. Constraints (8)– (10) sequentially calculate service start times at the points with respect to their time windows and operational time horizon of the cars. Constraints (11) delay the arrival time to next point j if there exist any transfer task just before point j while constraints (12) ensure the transfer task must be performed after the car arrives at the selected hub. Constraints (14) and (15) assign a single vessel to hub p only if there exists a transfer task decision at that hub. If no transfer task is assigned to a hub p immediately after i, then all second echelon constraints regarding this task become redundant. Constraints (16) indicate that the number of leaving and returning vessels to the waste centre must be equal and not larger than the fleet size. Constraints (17) ensure that the waste load for a transfer task must be at least the amount of collected waste on the car after serving last point i just before the transfer task occurs while (18) indicate the waste load on the vessel while performing transfer tasks. (19)-(21) state temporal limitations for transfer tasks. Finally, (22) - (26) define ranges for each decision variable.

Modelling one-to-one transfers

A hub can only perform one transfer task at a time, meaning that any two operations cannot overlap. Let f_{ij} be the time difference between the service start time of the transfer tasks requested immediately after collecting node i and j. If they are assigned to the same hub p, then we need to ensure that they need to be at least U units of time distant away from each other in order to finish one before starting the other. The temporal distance between two operations assigned to the same hub is equal to:

$$|u_i - u_j| \geq U(v_{ip} + v_{jp} - 1) \qquad i,j \in C, i \neq j, p \in S \qquad (27)$$

It can be linearized such that:

$$u_i - u_j \leq f_{ij} \qquad i,j \in C, i < j \qquad (28)$$

$$u_j - u_i \leq f_{ij} \qquad i,j \in C, i < j \qquad (29)$$

$$f_{ij} = f_{ji} \qquad i,j \in C, i \neq j \qquad (30)$$

$$f_{ij} \geq U(v_{ip} + v_{jp} - 1) \qquad i,j \in C, i < j, p \in S \qquad (31)$$

3. COMPUTATIONAL EXPERIMENTS

The proposed IWLT system, where cars and vessels operate in synchronization, is referred to as a two-echelon VRP with flexible vessels system (2-echelon-F) and evaluated with respect to three benchmarks: single echelon VRP with large trucks (1-echelon-T), single echelon VRP with small cars (1-echelon-C), and two-echelon VRP with stationary barges (2-echelon-S) system.

The models are implemented in a computer with Intel Core(TM) i7-3820 3.60 GHz and 32 GB RAM. They are solved by a commercial solver, CPLEX 12.10. The computation time limit is set to an hour for every instance.

Only large trucks: 1-echelon-T

To assess the proposed IWLT collection system, the traditional collection system is modeled assuming that large garbage trucks start from a depot in the city, collect waste, deliver it to the waste centre and return to the depot. It is formulated as a capacitated VRP with time windows considering the collection hours of the neighbourhoods. The proposed model by Bard, Kontoravdis and Yu (2002) is modified to include the trip to the waste centre at the end of each route before returning to the depot.

Only small electric cars: 1-echelon-C

Since large trucks will be removed from the streets by 2025 (Amsterdam.nl, 2019), another option is to use smaller electric cars instead of large trucks. They are allowed to perform multiple trip to the waste centre due to their relatively smaller capacities with respect to total waste. The model used in *1-echelon-T* system is modified to include multi-trip for the vehicles such that:

$$m_j \geq m_i + q_j - Q_1(1 - x_{ij} + v_i) \qquad i,j \in C, i \neq j \qquad (32)$$

$$h_i + s_i + t_{ij} + \varepsilon_i + Uv_i \leq h_j + M(1 - x_{ij}) \qquad i,j \in C, i \neq j \qquad (33)$$

$$\varepsilon_i \geq (c_{iw} + c_{wj} - c_{ij})(x_{ij} + v_i - 1) \qquad i \in C, j \in C_d, i \neq j \qquad (34)$$

Let m_i be the load on the car after collecting the waste point i, v_i decide whether there is a waste centre visit immediately after i and ε_i be the additional travel time to the waste centre. The cost of additional travel time (ε_i) is also added to the objective as a part of travel cost.

Stationary barges: 2-echelon-S

In this case, large barges are placed along the canals as temporary dump sites for the cars. Instead of delivering the collected waste to the waste centre as in the traditional setting or to the vessels as in the proposed setting, the cars dump the waste into these barges that are placed at a hub during the collection hours. The barges are taken to the waste centre by tugboats when they are full or no longer needed. The number of barges is assigned such that the waste generated in the city can be contained, $b_n = \lceil \frac{\sum_{i \in C} q_i}{Q_b} \rceil$ where Q_b is the capacity of a barge. The objective still includes the travel cost of the tugboats to place the barges to the selected hubs and take them back to the waste centre in order to account for the water level logistic costs in the IWLT setting. The proposed 2E-MTVRPTW-SS formulation is modified as follows:

$$v_{ip} \leq z_p \qquad i \in C, p \in S \qquad (35)$$

$$\sum_{p \in S} z_p = b_n = K_2 \qquad (36)$$

$$y_{ip,jr} = 0 \qquad i,j \in C, p,r \in S, p \neq r \qquad (37)$$

Constraints (35) allow the cars to use selected hubs as dump sites while constraints (36) ensure that at most b_n hubs are selected. Constraints (37) prevent inter-movements between hubs meaning that they can only be placed at a single hub. Note that these constraints are added to the model explained in Section 2 and subject to the hub capacity, multi-trip, synchronization and time window constraints.

Test Instances

We use modified Solomon's VRPTW instances (Solomon, 1987) as proposed by Grangier et al. (2016) for geographical configuration. The only difference is in locating the hubs, where we choose hubs outside of the city while Grangier et al. (2016) locate them at the center of the network. Keeping the transfer operations away from the public is primarily motivated by hygienic concerns, noise and the lack of space in the city. Let x_{min}, x_{max}, y_{min}, and y_{max} be the minimum and maximum values of the coordinates of the nodes to collect. Four hubs are located at (x_{min},y_{min}), (x_{min},y_{max}), (x_{max},y_{min}), and (x_{max},y_{max}). The earliest and latest operational times of the hubs, and the waste centre are equal to the ones of the depot as given in the instances.

To better observe multiple trips and transfer tasks, the capacity of electric cars is set to 50 units

Table 2: Results on the instances with 10 waste points and four hubs derived from Solomon's VRPTW problems (Solomon, 1987)

		Street Level			Water Level		
		NV	Travel Time	Weighted Avg. Load	NV	Travel Time	Weighted Avg. Load
C	1-echelon-T	1	227,99 (base)	92,11 (base)	-	-	-
	1-echelon-C	1	392,28 (+72%)	26,52 (-71%)	-	-	-
	2-echelon-S	1	208,65 (-8%)	28,63 (-69%)	1	119,61	79,38
	2-echelon-F	1	181,16 (-21%)	28,19 (-69%)	1	148,24	106,47
R	1-echelon-T	1	277,71 (base)	84,24 (base)	-	-	-
	1-echelon-C	1,3	413,59 (+49%)	27,61 (-67%)	-	-	-
	2-echelon-S	1	263,82 (-5%)	31,02 (-63%)	1	120,44	86,45
	2-echelon-F	1	205,66 (-26%)	26,65 (-68%)	1	191,28	151,46
RC	1-echelon-T	1	209,88 (base)	136,57 (base)	-	-	-
	1-echelon-C	2	408,04 (+94%)	38,71 (-72%)	-	-	-
	2-echelon-S^f	2	250,48 (+19%)	42,02 (-69%)	1	62,43	120,63
	2-echelon-F^f	2	197,56 (-6%)	35,91 (-74%)	1	163,58	146,23

in 1-echelon-C, 2-echelon-S, and 2-echelon-F systems. The capacity of the trucks, barges and vessels are set to 250 units.

The objective is minimizing the number of trucks or cars first, and then minimizing the travel cost for 1-echelon-T and 1-echelon-C systems. Similarly for 2-echelon-S and 2-echelon-F systems, the first priority is to minimize the number of cars, then the travel cost. The cost of water-level logistics is also minimized in the same order but relatively less important than the street level cost such that the fixed cost of the cars (β_1) is set to 1000, the travel cost on the streets is equal to 1 while the fixed cost for the vessels (β_2) 100 and the travel cost is 0.1 of the travel times. The main motivation is to reduce the heavy movements and congestion on the streets. Lastly, U is assumed to be 150 time units.

For testing different approaches, we assume that waste points are the first ten nodes of Solomon class "2" instances with wide time windows and long scheduling horizons, which is more similar to the structure of the collection hours for neighbourhoods.

Results and Discussion

Table 2 summarizes the average results of the instances in each type for the problems with ten waste points for all approaches and four hubs for 2-echelon-S and 2-echelon-F systems. Based on the geographical distribution of the waste points, cases are divided into three categories: C type for clustered locations, R type for random locations, and RC type for randomly clustered locations. For both levels, *NV* is the number of the vehicles (cars, barges, or vessels), *Travel Time* is the total travel time of the vehicles on their own network, while *Weighted Avg. Load* is the weighted average of the load on the vehicles per travel time considering non-empty movements. All instances are solved to optimality except the ones labeled with superscript f, where the best feasible solutions are presented.

1-echelon-T system has typically been preferred by decision-makers for the advantage of easy and direct access to service areas, as well as larger capacity of trucks, which leads to fewer trucks needed for waste collection. Therefore, 1-echelon-T system cannot be beaten in terms of the number of vehicles for all instances as expected. 1-echelon-C system requires frequent visits to the waste centre due to the smaller capacity of electric cars, resulting in under-utilization of the working hours. It causes more cars to use in R type problems on average compared to 2-echelon-S and 2-echelon-F systems, where small cars also operate. 2-echelon IWLT systems can reduce the number of cars down to the number of trucks for R and C type problems, but failed to use less cars for RC type problems.

Travel Time for the street level represents the vehicle movements on the streets. The models, also, minimize the travel cost which is mostly proportional to the travel time. The results show that the proposed 2-echelon-F system reduces the burden on the road infrastructure by partially shifting the movements to inland waterways. It reduces the total travel time on the streets for all type of problems more than 2-echelon-S system which shows the added value of the flexibility.

The cost of waste collection in Amsterdam is not only about the logistic cost but also the damage on quay walls. 2-echelon-S system produces the largest values for *Weighted Avg. Load* among three systems, where the cars are used, compared to 1-echelon-T. 2-echelon-F system can achieve the lowest *Weighted Avg. Load* for almost all scenarios. It shows us 2-echelon-F system has the potential to reduce heavy street movements by providing cheaper solutions in terms of the fleet size, total street travel time and lightweight operating garbage cars.

4. CONCLUSIONS

In this study, we consider an integrated water- and land-based waste collection system that aims to remove heavy large garbage trucks from the streets to reduce the damage on the quay walls as well as the congestion. We provide a new formulation for the 2E-MTVRPTW-SS considering one-to-one transfers, and compare the proposed approach with three different benchmarks in terms of the fleet size, average travel time on the streets, and weighted average load of the vehicles per non-empty movements. The proposed system with synchronized mobile vessels and electric cars is shown to be a promising solution for the issues with the current system. It can reduce the total travel time of the garbage cars on the street by 18% and the weighted average loads of the cars by 70% on average across all scenarios without increasing the fleet size of the cars significantly even if they have way less capacities than the traditional garbage trucks.

The proposed model is a computationally heavy problem. Decomposition-based exact methods or heuristics can be developed for the problem to solve larger instances in order to gain more insights into the gains of such a system. The gains observed in small instances gives indications on the potential improvements that can be obtained for larger instances.

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