Exploring mobility networks inter-connectivity for an on-demand transshipment of goods in urban areas

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Abstract.
This work investigates the opportunity to exploit an on-demand goods transshipment service in urban areas. It relies on the usage of multi-modes transportation system which are partially or initially dedicated to mobility services. The innovative proposal is first characterized in link with the inter-connectivity needs and then its operability is modeled as a new transportation problem. In this case, we deal with a specific dynamic on-demand transshipment problem that is derived from the stacker crane problem with additional constraints on distance to travel and battery use. For this problem, we propose a dynamic matching strategy that solves efficiently the problem by managing the empty moves of the different type of vehicles traveling between different physical internet-enabled transit locations. An illustrative case is given to illustrate how the multi-modes transportation system could operate and to provide an initial evaluation of the economic and sustainability benefits of the approach in an urban context.

Keywords: Urban Mobility, Freight Transportation, Electric vehicles, transportation-on-demand, Physical Internet

1 Introduction

Transportation of goods in urban areas represents an important proportion of the total moves on a daily basis within cities. From residents's perspective, the main moves consist on transporting goods supplied from groceries or from retail stores, and on moving out to nearby pickup points to collect online ordered products. From logistics companies's perspective, the main moves are the well-known last mile deliveries that are nowadays more and more under pressure with the higher requirements of the online retailing system. With the expected surge in small-package delivery services, these actors represent a vital link between the globally dispersed suppliers and the city residents and their will be challenged in the future for their efficiency, service level, ecological footprint and social impact on the city. Furthermore, urban population is steadily growing and we predict that by 2025 more than 4.4 billion of people will be living in urban areas[1]. New mega cities are appearing in many countries especially in Latin America and Asia, which will rise to over 85% the world population living in cities by 2050. These figures are a source of preoccupation for city planners and for large scale logistics companies.

On the other hand, recent experiences in City Logistics (CL) have shown that enhancing only the traffic and parking regulation is no longer efficient to deal with all urban issues [3] and that a more global vision on people mobility and goods delivery is desired in terms of sharing transportation infrastructure, vehicles and routes. It is within this context that the concept of physical internet (PI) was proposed as a novel and open framework in order to connect within the same system humans, objects, networks and social actors. Consequently, a more distributed and sustainable logistic network could be reached enabling the easy access of goods. In fact and within the PI vision, goods could be moved handled and stored via a logistics web that corresponds to a network of logistic networks. Thus, the implementation of the PI framework would

[1]Source: UN World Urbanization Prospects, World Business Council for Sustainable Development

enable to move toward a more interconnected and decentralized transportation service where goods are encapsulated in smart easy to handle and modular PI-containers. Within an urban area, inter-connectivity would be strongly enhanced thanks to the usage of a high number of PI-transit hubs and the usage of several transportation options to ensure efficient and fast transshipment moves between all the origin-destination pairs of the PI-transit hubs network. Based on all these features, the introduction of the Interconnected City Logistics (ICL) enables a more efficient and sustainable way to handle and transport goods [6].

Within this context, many researchers considered recently the investigation of innovative solutions with the modeling of shared autonomous vehicles and taxi for moving persons ([4]) as well as proposing freight rapid transit systems running on guideways ([7]) or shared Cargo-bike systems ([12]). Additionally, new sharing-based business models emerged in the recent years (Autolib, Bluecar, Zipcar, Car2go,...) in order to find alternative usage of city vehicles during usual obsolescence[2] periods such as working sessions and the night window. Also, some industrials started to investigate opportunities in developing new innovative delivery solutions such as Drone-based deliveries, Uber-based services, etc. Furthermore, a keen interest was recently dedicated to find new business models and practices for urban mobility based on the usage of autonomous vehicles (AV). AVs represent an intelligent transportation system that offers the opportunity to provide an on-demand transportation service which balances efficiently the fleet of its vehicles in order to better match the demand of its users. Several economic[3] and transportation[4] oriented studies were recently published on the potential benefits of the use of multi-modal transportation system deployment in the near future. However, to the best our knowledge, none of these studies, considered the integration of goods transportation needs with persons urban mobility as a joint solution for an enhanced urban system.

This work attempts, first, to investigate the feasibility of goods transshipment with a joint freight and mobility transportation system in urban areas; and second, to propose modeling and solution approaches of the associated multi-modal on-demand transshipment problem. It builds on the opportunity to use different existent on-demand transportation services with AV, Cargo-bike, public or private fleet available on-demand, etc., to transship Pi-containers from a Pi-transit hub to another. Such proposal should be seen as complementary to the classical vehicle routing problem-based solutions in urban areas and when planned globally jointly with the latter could be characterized as a multi-modes routing plan. This is made with the surrounding objective to increase the city sustainability by reducing the congestion level, by limiting the number and moves of logistics operators, and by minimizing, when desired, residents's moves to collect ordered goods. However, only few studies expressed these opportunities ([1]) and attempted to model this specific on-demand transportation problem ([13] and [11]).

The remainder of this paper is organized as follows. Section 2 links the on-demand transshipment problem to more known variants of the vehicle routing problem and then, proposes a modeling and solution approaches. In Section 3, an illustrative example and preliminaries results are provided to analyze the performance of the proposal in an urban context. Finally, conclusion and future work are provided.

2 Characterization of the on-demand transshipment problem

Based on a typical urban context, this section first describes how alternative delivery of goods could be operated taking into account the existent mobility network and the connectivity capabilities for ensuring an on-demand service. Next, it shows how the operational on-demand goods transshipment problem could be formulated as an extension of the vehicle routing problem with pickup and delivery operations. This paper characterizes, at a day to day level, the goods transshipment problem which involves decisions related to the different transportation services to use and to locate with the aim to provide a satisfactory service level as well as reduce total empty moves. The transportation context considered in this work assumes stochastic travel time between different locations, which affects the transportation options travels, their capacity as well as the electric vehicles battery autonomy. In addition, it shapes the fleet availability per period of the novel transportation services using a random variable which makes their number and location uncertain. As we will characterize it later on, all these features give rise to a specific extension of the well-known pick-up

[2]Estimations provided hat a vehicle sits unused on average for 22 hours a day.
[3]Rand Corporation
[4]DHL -Self Driving Vehicles Report.

and delivery problem (PDP).
In what follows, we consider that the goods transshipment service consists on collecting goods (referred hereafter as a single item) from a Pi-transit locations and transporting it to some other Pi-transit locations within the pre-established urban network. The mobility network considered includes various transportation options that are mainly dedicated to persons service, but could be available for goods dedicated which are: on demand vehicle (uber-like service), Cargo-Bike and Automated Vehicles (AV) to on-demand transportation requests.

Figure 1 illustrates a city context in which a set of predefined itineraries are designed to run the different type of vehicles where each specific type of vehicles has its own itinerary between any pair of Pi-transit locations. The different type of vehicles are used on a daily basis, at specific time windows. As illustrated, the proposed system is intended to operate a set of mobility services in order to answer to requests to pickup goods from a predefined Pi-transit location and to deliver them to an alternative Pi-transit location. This conceptual representation assumes the availability of enhanced handling technologies at the Pi-transit locations to automate and speed-up the process, as it is preconized in the Physical Internet manifesto [2]. One should mention that the idea of introducing several novel transportation services within the physical internet context must be positioned in an interconnected way with other existing transportation modes (i.e. complementary with existing practices and usual transportation services). This assumes that design decisions related to the different modes's infrastructure is already implemented within an urban area.

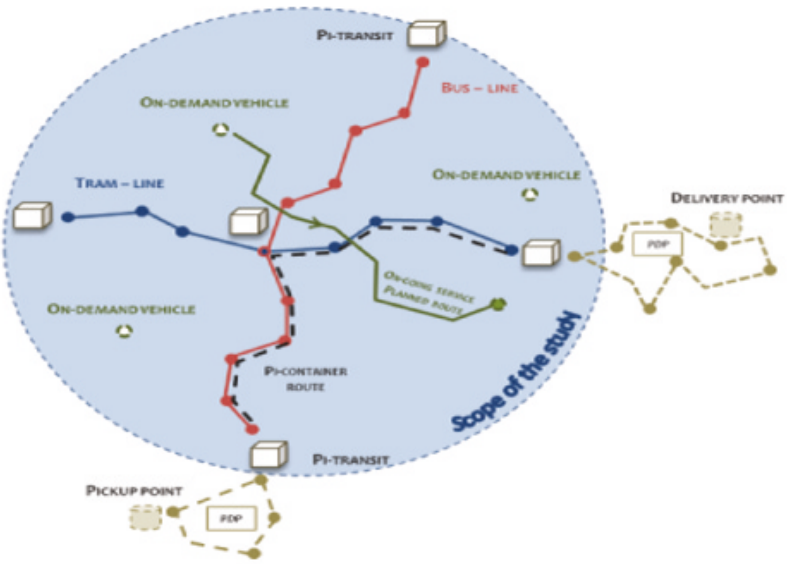

Figure 1: An illustration of a multi-modes good transportation system within physical internet context.

2.1 Correspondence between the transshipment On-demand problem and the Classical PDP

The PDP constitutes an important branch under the class of vehicle routing problems. It consists mainly on moving objects or people between different locations which has many real world applications. The PDP could be divided into three major subclasses [5] namely the many to many PDP, the one to many to one PDP and the one to one PDP. Typically, there are two major classes under the latter one to one PDP problem, namely: the dial a ride problem (DARP) and the Stacker Crane Problem (SCP), which are well studied in the literature. As for SCP, the first work related to it that appeared in the literature in 1976 in [8] where the authors described this NP hard problem and proposed a c-approximation approach to solve it. In [10], Laporte used techniques for the Travel Salesman Problem (TSP) to solve instances of SCP. Recently, Srour and Van Velde [9] performed a statistical study to prove that the SCP is as hard as at least the Asymmetric TSP.

Since the SCP is a route optimization problem behind the transportation-on-demand system, our studied problem shares many similarities with the SCP since a vehicle could only serve one request at a time. In addition, our model approach considers the use of multiple type of vehicles on the same shared network, and adds many other constraints such as time windows, capacity and battery constraints which impose limited time service and distance constraints to the problem. With all these features, this paper extends the traditional SCP with a dynamic version minimizing traveled distance and waiting time of transportation requests while considering a variant travel time in the urban area.

2.2 Modeling Approach

Taking into account all the business context features described above, we could now derive the corresponding model that focuses on the economic and environmental issues when operating the goods's transshipment. In fact as our proposal offers an on-demand transportation service, it could results on a large amount of empty vehicles moves on the network. This latter issue represents a huge loss in term of energy consumption (an economic loss) as well as carbon emissions (an environmental loss). So our modeling approach is interested to focus on a transshipment service that reduces globally the empty movements and that select the more sustainable transportation options, with the commitment to a satisfactory service level. The following modeling features are considered:

- **Multi-Period setting**: In a typical working day, the system could face several transportation issues related to congestion, rush hours, variable level of requests, etc... Consequently, a typical working day would be divided into several periods' where each one is characterized by its length, congestion and demand level. Given that, the entire horizon would be shaped into several discrete set of periods. For each period, the system must decide which Pi-container to serve first by which vehicle at a minimum cost subject to several constraints. When a Pi-container is received at one of the PI-transit location, a vehicle would either stay at its current position, return to the depot to recharge its battery if needed to move empty to serve the received transportation request.

- **Heterogeneous fleet**: the fleet of vehicle considered in our multi-modes goods's transportation system would include the following types: a) Electric AV for goods transportation with limited battery capacity, b) available shared vehicles such as Uber, Autolib, Bluecar initially dedicated for moving passengers but are willing in specific periods to move small PI-containers, c) Cargo-bike, which are on-demand also and without carbon footprint. Let M be a set that defines the different transportation modes used in our system. Each transportation mode is denoted by m G M. We suppose here to have a set of Pi-transit locations where vehicles could wait for good's transportation request and that their availability varies from a period to another due to their external usage for mobility. Also, we assume that the paths between each pair of Pi-transit locations and for each transportation mode is predetermined in the urban area, which means that the distance between each pair of Pi- transit location and for each transportation mode is know a priori.

- **One single capacity vehicles**: In order to guarantee an on-time transportation service, the different vehicles used in our context are treated as a one unit transportation capacity. This is argued by the fact that urban delivery are in general small sized parcels and that it fit with the small size of the different vehicles used in our context. This means that we suppose that the vehicles used have a maximum capacity of serving one transportation request between two Pi-transit locations. With these different characteristics in mind, continuous arrival of transportation's requests of moving PI-containers from one PI-transit location to another would be received incrementally.

For the proposed system a cost would be associated with the decision of dispatching a vehicle to serve a transportation request. This cost is composed of the energy used while moving empty to satisfy the transportation request in addition to the energy needed to serve the transportation request. However, the energy consumed while moving empty would be considered wasted as it represents the main drawback of on-demand transportation systems. In fact, the itinerary between two Pi- transit locations A and B could be different based on the transportation mode used to move between these two locations. These distances are defined for each transportation mode M using a known r_M matrix. However, we assume that within a working day, the PI-network characteristics and input could undergo several changes due to several factors such as congestion and the availability of the fleet of vehicles. We denote by ft the set of vehicles and each vehicle $v_i \in ft$ has its own battery capacity, denoted by B. The AVs can only recharge their batteries in a one single location where initially all the AV are located. As for the cargo-bike's or shared vehicles, constraints related to this transportation's mode are in the form of loading capacity constraints.

As mentioned, we suppose that the users goods's transportation requests are gradually received over time and variant based on a Poisson process. When a customer's transportation request p_i is received, it is defined by the following characteristics: i) Departure Pi-transit location DL_i, ii) Destination Pi-transit location AL_i and Time of arrival AT_i. As we considered the periods to be discrete, a decision needs to be made at each period corresponding to τ based on the new updated state of the system. These different periodic decisions has to be made independently of the future state of the system but in a manner that take into account the previous period decisions. Consequently at each new period τ, the state of the system would be updated based on the dispatching decisions that has been taken previously. In fact at each period, the system would face new arrival of transportation requests, unserved transportation requests from the previous periods as well as an update on the states of the different vehicles in the system. Therefore, each period τ would be linked to the previous period $\tau - 1$ as well as to the next period $\tau + 1$. More specifically, at each period τ new transportation demands are received. The set of non satisfied transportation demands from the previous period $\tau - 1$ would be propagated to the period τ. Unsatisfied transportation requests occurs due to the limited fleet size of available vehicles. Therefore, unsatisfied transportation demand at period τ would need to wait to the next period $\tau + 1$ in order to be fulfilled. Therefore at period τ, the system would need to satisfy a set of demand composed of newly received transportation requests as well as non satisfied requests from the previous period. At the beginning of each period τ, the status of the different vehicles would also be updated as new empty vehicles would be available. The new empty vehicles include vehicles arriving to their destination, AV becoming available after charging their batteries and new empty vehicles becoming available.

Based on this description, a central decision and dispatching system needs to decide which vehicles should be assigned to which transportation's request at a minimum objective of empty moves for each period τ. To this end and to solve efficiently our problem, a forward periodic-optimization approach is proposed. It builds on the resolution of a sequence of linear programs that are solvable and relies on a dynamic matching reformulation that enhances the solvability of the modeling approach proposed.

2.3 The Solution Approach

In this section, we present our solution approach to solve the on-demand transshipment problem. To this end, we present a dynamic matching strategy (DMS) based on a graph representation of the problem that enhances its solvability. Earlier version of this strategy was proposed for solving a dynamic routing problem formulation of a Personal Rapid Transit (PRT) and Freight Rapid Transit (FRT) joint system in an urban area [7]. In this section, we are proposing to extend this strategy to our general context of moving goods using several transportation modes with time windows constraints. The objective of our DMS is to move idle vehicles reactively to the goods demands movements in urban area. In fact, the movements of vehicles from their current PI-transit location to the transportation request's PI-transit location is costly in term of empty moves. Empty moves within the system are considered as a wasted transportation capacity as vehicles moving empty would generated a loss in term of energy consumption. Consequently, our objective is to reduce the transportation's cost of the related empty moves within the system while offering a high level of transportation service. Based on our approach, the whole working day would be divided into periods on which we apply our DMS in order to dispatch available vehicles to goods transportation's requests. The dispatching of the vehicles needs to be made based on the different constraints related to vehicles' types. For this purpose, we propose a graph based modeling of our dispatching problem at each period τ.
Let us define a bipartite graph $G = \{\vec{V}, \vec{E}\}$. $\vec{V} = S \bigcup T.S$ is a set of nodes where $s_i \in S$ represents an available empty free vehicles in the system. We also have $dp \in S$ which is a node representing the different vehicles

in the charging location (AVs, electric vehicles/trucks). Then, let us note $S^* = \vec{S} \backslash dp$. Let us also note β_i is the remaining energy in the battery of the vehicle i at time t. As for the set T, it represents the nodes representing the different good transportation's requests. The set of edges E is defined by the following rules:

- for each pair of nodes (s_i, t_j), where $s_i \in S^*$ and s_i is an AV, we add an arc (i, j) only if β_i is great of equal to the energy needed to go and move the transportation request t_j to its destination and go back to the charging location of AVs. Otherwise in the case of Cargo-bike, we add an arc (i, j). (i, j) has a cost denoted c_{ij} equals to the time needed to move empty (the empty move) from the current PI-transit location of s_i to the PI-transit location t_j.
- for all nodes in T, we add an arc (dp, t_j) that has a cost denoted c_{ij} equals to the time needed to move empty from the charging location of AV to the PI-transit location t_j..

Moreover, at each period and after constructing the graph G, we need to find the minimum cost matching option in G. By doing so, we would find the minimum empty movements for the system to satisfy the set of waiting transportation good's requests.
Following this graph based modeling of our problem, we present next a mathematical based model encompassed in our . The presented mathematical formulation would be used to find the minimum set of empty moves at each time period t.
More specifically, we present two flow-based mathematical formulations for solving our assignment problem based on the cardinality of sets S and T. We first introduce the following integer variable:

$$x_{ij} = \begin{cases} 1 & \text{if vehicle } s_i \text{ is dispatched empty to serve transportation request } t_j \\ 0 & \text{otherwise} \end{cases}$$

If $|S| < |T|$, we solve the linear program (1)-(3), else we solve the linear program (4)-(6).

$$\textbf{DMS(1)}: \qquad \text{Minimize} \sum_{(i,j) \in E} c_{ij} x_{ij} \tag{1}$$

$$\sum_{j \in \delta^+(i)} x_{ij} = 1 \quad \forall i \in S^* \tag{2}$$

$$\sum_{j \in \delta^-(i)} x_{ji} \leq 1 \quad \forall i \in T^* \tag{3}$$

$$\textbf{DMS(2)}: \qquad \text{Minimize} \sum_{(i,j) \in E} c_{ij} x_{ij} \tag{4}$$

$$\sum_{j \in \delta^+(i)} x_{ij} \leq 1 \quad \forall i \in S^* \tag{5}$$

$$\sum_{j \in \delta^-(i)} x_{ji} = 1 \quad \forall i \in T^* \tag{6}$$

Objectives (1) and (4) propose to minimize the set of empty moves in the system. In fact, the cost c_{ij} represents the empty move expressed in total traveled time between the location of a vehicle and a transportation's request. x_{ij} represents if the edge (i, j) is in the final solution or not. Consequently, the objective function would reduce the total empty moves of the system while satisfying the set of waiting transportation's requests. Constraints (2) and (6) require that each node must be in the final solution exactly once. Constraints (5) and (3) require that each node may or may not be in the final solution. If there are not enough empty vehicles in the network, we use a first-in first-served rule whereby the transportation requests which has waited the longest will be served first.

3 Illustrative Example

To illustrate our problem modeling and solution approaches, this section considers a typical urban context related to a mid-size city which is inspired from the Corby routing use case in the UK. As illustrated in Figure 1, this use case represents a set of dedicated itineraries for electric vehicles usage with a number of location points dedicated to goods pick-up and delivery. To test the validity of the proposed strategy, we use simulation techniques and the procedure was implemented in C++ language to run the experiments. The instances generated for this case study are based on three main dimensions:

- Demand scenario: The demand scenarios are based on request rate from an origin on-street parking location i to a destination on-street parking location j. These requests are supposed to follow a Poisson Process rate $\lambda_{ij} \in [0.789, 17.902]$. These rates are generated randomly based on specific rate's range already existent in the literature. Overall 20 scenarios were generated along a simulation horizon of 2 hours.
- Network topology: The distance matrix related to our studied use's case was generated based on the Corby use case[5]. This network has 15 loading/unloading locations that correspond here to PI-transit locations.
- Fleet size: we supposed that we have a variant fleet of vehicles. To model the variability of the availability of the vehicles, we considered three levels namely highly, medium and low available. The high level of availability of vehicles is considered at the first third of the simulated period. The low level of availability of vehicles is considered at the second third of the simulated period where only 50% of the initial fleet at $\tau = 0$ is available. The medium level of availability of vehicles is considered at the last third of the simulated period where only 70% of the initial fleet at $\tau = 0$ is available.

We mention also, that we tested our multi-modes transportation model with varying at each time the travel time based on the period of the day by including a congestion factor.
With these dimensions, the various scenarios were tested in order to appreciate the potential benefit of using such multi-modes transportation system for the transshipment of goods in urban areas. Therefore, we tested three configurations: (a) only an on-demand truck system (with a fleet of 50 vehicles) can be used; (b) on-demand truck system jointly with Cargo-bike (50 vehicles + 50 bikes) can be used; and (c) on demand truck system jointly with Cargo-bike and AVs (in total a fleet of 150) can be used. The comparison were made based on the total empty moves of the vehicles which could be considered as a wasted transportation capacity of the system. Results are presented in Figure 2.

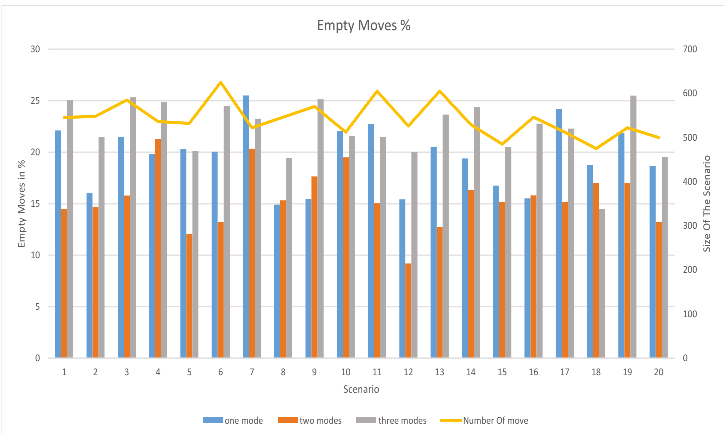

Figure 2: Impact on the including multi-modes transportation system for the transshipment of goods in urban areas

This figure underlines the good performance of the transshipment system when several modes are proposed. The configuration (c) based on the joint of the three modes has an average empty moves of 22.26 %. From this figure, we could note that when increasing the number of alternative modes available from one to two modes, this incurs a reduction of the percentage of empty moves from 19.58% to 15.55%. We mention that the largest gap between the one mode and two modes systems occurs in demand scenario 17 (about 9.06%) and the smallest gap occurs in demand scenario 2 (about 1.33%) in favor of the two-modes transportation system. This is due to the fact that the usage of cargo-bike system is an efficient on-demand transportation tool which doesn't necessitate battery charging moves. Conversely when increasing from

[5] Public data are available in ATS/CityMobil source: http://www.ultraprt.com/prt/implementation/simulation/

configuration (b) to (c), we noticed an increase in the percentage of the total empty moves as AVs would moves periodically empty between PI-transit locations and the charging location. However, one could observe that this increase in the fleet in the network provides a better transshipment service with the usage of a sustainable mode. With regards to the service, the average waiting time for the total received requests is calculated for each configuration tested. It provides an average waiting time in seconds of 111.99 , 98.88 and 65.85 for configurations (a), (b) and (c), respectively. All these results underline the benefits of operating an existing mobility system to enhance the transshipment of goods in an urban area from an economic and an ecologic perspectives.

4 Conclusions and Future Works

In this paper, we proposed a novel approach to transship goods in an urban area based on the joint use of Cargo- bike, AV, electric vehicles/trucks in an on-demand mode. The modeling approach relies on a graph-based reformulation of the SCP with multiple transportation options, time windows and distance constraints. The solution approach is based on a forward periodic approach that solves with CPLEX periodically the service assignment sub-problem. Based on the case study of an urban mobility network in the UK, we proposed preliminaries results that confirmed the efficiency of our proposal in terms of service and in terms of sustainability. Extended experiments are under development in order to further show the feasibility of our proposal and the performance levers that it could provide in the future. As a future work, the model can be up-scaled, considering several city depots, more type of vehicles/services in an on demand mode.

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