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INTEGRATED MATHEMATICAL MODELING OF AN ACCESS NETWORK AND A BACKBONE NETWORK FOR THE PHYSICAL INTERNET

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ABSTRACT

As consumer needs continue to evolve, supply chains must improve and adapt by taking advantage of technological advances. Additionally, supply chains must sustainably meet those above-mentioned challenges and without further costs. In this paper, we support the Physical Internet as a framework for the development of future logistics networks. Respectively, we have addressed the design of a network for the implementation of the Physical Internet. This network allows, on the one hand, to take advantage of all optimization possibilities and on the other hand, enables the interconnection with the existing logistic networks through the π-gateways, which are an integral part of this future network. To address these characteristics, we have retained the approach that combines an access network and a backbone network without restriction of the networks' topology. Therefore, we have combined the median p-hub problem with the multi-commodity flow problem. The mathematical model we provide represents the physical Internet network as a graph. It considers and distinguishes the setup costs of the different nodes, the setup costs of the different links and their usage costs. Through the additional parameters and constraints presented, the model can adapt by changing the network configuration if necessary. The resolution of the model is not covered in this work. The main contribution of this work is that it is the first to introduce an access and backbone network approach for the design of the Physical Internet. Moreover, and unlike most contributions on this topic, it provides an integrated design of the access network and the backbone network.

Keywords: *Physical Internet, Access/Backbone networks, Logistics, Location Problem, Mixed Integer Programming*

1. INTRODUCTION

Technological progress and the continuous evolution of consumer needs challenge supply chains to constantly adapt and improve. Furthermore, globalization presents both threats and opportunities. As competition between companies increases and markets tighten between a few key players, the opportunities for pooling and collaboration increase and become the only way to progress, or even survive. Consumers are demanding increasingly personalized products, and this represents a real challenge for mass production practices. Thus, companies are pushed to finalize the production as close as possible to the customers. These are challenges that supply chains need to handle in a sustainable way and, most importantly, without additional costs.

To face this context, a new concept has been proposed that is totally disruptive to the current conception and perception of supply chains [1]. This concept is called the Physical Internet. Inspired and supported by the Digital Internet, the Physical Internet aims at creating a global network for the exchange of goods. Exchanges made in π-containers. These are standard, modular and intelligent containers that allow products to be moved easily between shipper and end customer [2].

To build a Physical Internet network, it is necessary to identify the intermediate nodes that will be used to move products between an origin and a destination. This is a location problem with two special aspects. First, the number of intermediate nodes is variable depending on the optimization opportunities. Second, the interconnection with classical logistics networks requires special nodes that act as access points to the Physical Internet. Both aspects must be considered in the design of the network. From this perspective, we aim at answering three questions: (1) What are the characteristics of the proposed Physical Internet network? (2) What is the configuration of this network? (3) What is the mathematical model that respects this configuration and preserves the requested features?

The remainder of this article is divided into four sections. The second section is devoted to the literature review. It includes all the publications of the Physical Internet that deal with the localization problem (until 2022). It also discusses the literature about the configuration of communication networks and node location problems with a focus on configurations that are compatible with our work. The third section details the mathematical model we propose and specifies how to adapt the model formulation to support special scenarios. Solving the model is not covered in this work. The fourth section addresses the discussion and research perspectives that the proposed network is opening. The fifth section is the conclusion.

2. LITERATURE REVIEW

2.1. The Physical Internet and The Location Problems

In order to fully benefit from the Physical Internet, it is necessary to create a network that is as consistent as possible with the vision presented in [1]–[3]. Aside from the technical and technological constraints, the implementation of a Physical Internet network can start with the location of the different π-nodes that will build it. This problem can be modeled generally as a location problem with a major precision: the number of nodes to visit between the origin and the destination is not fixed. The number of intermediate nodes depends on the opportunities for mutualization and on the potential gain to be realized with these opportunities. It is important to consider that in the spirit of the Physical Internet, we must imagine a network shared by the various economic actors who share the need to transport goods. A perception where the networks are more likely computer networks than current logistics networks.

The review of the Physical Internet literature reveals that only a few publications have addressed the node location problem but not with the vision we present in this work. [4] presents a deterministic model of a network of nodes with capacity constraints. The model allows the selection of nodes that minimize transportation costs, empty return costs, and facility management and depreciation costs. However, this model only considers nodes immediately adjacent to the origin and destination. Contribution [5] provides a multi-tier facility location model with capacity constraints. The model locates nodes that minimize facility construction costs and transportation costs. But the model deals with only two levels. The first level is the flow between plants and warehouses. The second one covers the flows between the warehouses and the customers. [6] gives a node location model with multiple allocations and considers capacity constraints. The model selects nodes that minimize facility construction costs and transportation costs. The calculated transportation cost consists of the cost of routing from origins to a first node, then from origins to two consecutive nodes, and finally from origins to their destinations through a single intermediate node. At most two intermediate nodes are considered in this modeling. The work [7] presents a model for shipping line networks. The model is based on the multi-commodity flow problem. It determines the nodes that minimize the network cost and the cost of moving containers through the network. The model evaluates circuits with a variable number of intermediate nodes creating a network that connects multiple ports. However, it does not consider the routing of products from their origins and to their final destinations. [8] presents the design of a distribution network. The model selects nodes to open in a way that minimizes warehouse setup costs, holding costs, and transportation costs. The work features a two-echelon model. The first echelon contains the nodes between the factories and the nodes of the second echelon. The second echelon is composed of the nodes that link the first echelon to the demand areas. The model does not accept flows between nodes in the same echelon. It only considers a maximum of two intermediate nodes between an origin and a destination. [9] introduces the design of a distribution network. The model identifies nodes that minimize warehouse setup costs and transportation costs. The model provides a single intermediate level between the factory and the customer's city. [10] presents a model for a two-tier distribution network. The model assigns demand areas to nodes that will serve them to minimize set-up costs, terminal operational costs, and transportation costs. The model provides a single intermediate level between the origin of the goods and the customer.

The literature on the Physical Internet is mainly based on existing logistic networks. According to [11], the literature still considers a directional flow from an origin to a destination (Figure 1). This limits the designs and hence the proposed mathematical models. We believe that achieving the levels of optimization expected in the Physical Internet can only be achieved by changing the perception of the logistics network as supported by [11]. In the Physical Internet, both the supplier and the customer are network users. In this context, even the flows of raw materials or reverse logistics will be considered as simple flows between two users. Therefore, they can be pooled with the other flows without the need to consider them as special cases. The network we present allows us to take care of these gaps.

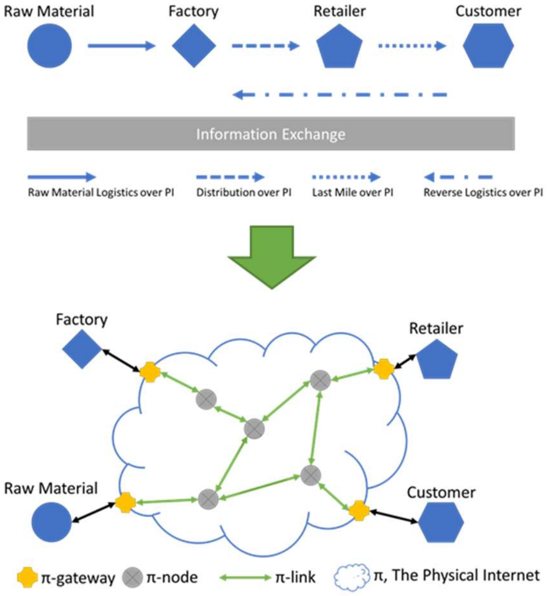

Figure 1. The current perception (top) and the network perception (bottom) of The Physical Internet [11]

Moreover, the implementation of a Physical Internet network requires potentially new and different facilities compared to current logistics facilities. Thus, to use the current warehouses, adaptations would be necessary. In this sense, customers are even less able to use a Physical Internet network natively. This raises an interconnection problem between the current logistics networks and the Physical Internet. This problem can be solved by setting up π-gateways [2]. These special nodes serve as interfaces between the physical Internet network and a classical logistics network. They are required access points to the Physical Internet network from a classical logistics network or to exit the Physical Internet network to a classical logistics network. The π-gateways play an important key function in our design. Indeed, they allow to link classical networks to a Physical Internet network. This link allows to adapt the goods in terms of packaging (containerization) and in terms of identification (information management) to allow them to circulate in the Physical Internet in an optimal way. Obviously, goods that are compatible with the Physical Internet will not need to be adapted. This way, this mechanism could allow the gradual adoption of the Physical Internet and enable its coexistence with the current logistics networks. Once inside the Physical Internet, the goods are moved through the π-nodes where the transportation is multimodal. The π-nodes, provide routing and/or storage functions as needed.

Briefly, the objective is to design and model a Physical Internet network that minimizes setup and routing costs. This optimization will only be possible if the model supports any number of intermediate nodes between each origin/destination pair. To solve the interconnection problem between the classical logistics networks and the Physical Internet network, the π-gateways must be used and therefore considered by the model. These are the characteristics of the Physical Internet network as we conceive it and thus the answer to the first question.

2.2. Communication Network Configuration and Location Problems

When circuit and message switching were first introduced, the switching centers were connected by links called trunks or backbones [12]. Then came packet switching [13]. According to [14], the first publication on the topic describes a network that distinguishes between the main nodes of the network and the computers that serve as access interfaces to user equipment [15]. The nodes have specific interconnection equipment and can establish several links, which is superior to the links that can be established by the other equipment in the network. These nodes communicate with each other through a specific protocol. The interface computers have two main functions: (1) to control the communication between the connected devices and (2) to reconcile the format requested by the main nodes with the highly variable requirements of the users. [16] presents a network incorporating new types of nodes with regional nodes "whose function is to route messages from tributary nodes onto the backbone or high-density links". Here the tributary nodes take over the connection to the users' equipment. It should also be noted that the capacity of the backbone is understood to be greater than the capacity of the other links in the network.

As communication networks develop and become more complex, the concepts of backbone network and tributary network are used to designate respectively the main network and the interface network to which users connect. The latter is also called the access network. This split between the backbone and the access network has the following advantages, among others:

- Simplification of the network design and increasing the capacity to adapt to technical changes and optimizations [15]. In the case of the Physical Internet, this simplification could allow for faster progress in the deployment of the network. The adaptive capabilities could allow for the gradual development of the Physical Internet as it can coexist with conventional logistics networks. This could further accelerate the adoption and deployment of the Physical Internet.
- Limiting the impact of the evolution of the main network on the users [15]. It would thus be possible to start with a basic Physical Internet network and to gradually evolve it (in terms of capacity, speed, support of new types of flows, etc.) with complete transparency for the users and without having to upgrade all the existing logistic networks.
- Interconnecting heterogeneous networks through interface computers [15] or gateways [15], [17]. These essential devices are the equivalents of π-gateways. Indeed, they would be the key to the exchanges between the different logistic networks (Physical Internet, conventional, proprietary, networks of different maturity levels, etc.). This way, π-gateways could offer the network the ability to progressively expand or upgrade sections of the network without impacting users by simply placing π-gateways between old and new sections of the network.
- The ability of the core network to support more flow types (data, voice, video, etc.) [14] than the users without compatibility requirements with regard to the users. In the case of the Physical Internet, the core network can support both products (with specific management of dry, positive, negative, dangerous, etc.) and people while serving networks that manage only one type at a time.

Accordingly, the Physical Internet network that we consider consists of a main network constituted by the π-nodes with their different specialties (refer to [2] for more details), an access network based on the π-gateway and the network of uses that will be the clients of the Physical Internet. The closest design to this kind of networks is the access and backbone network design. The latest literature review on this topic [18] points out that most often the design of access networks and backbone networks are done separately. The reason for this separation is often due to the complexity of the problem, but also to the applications considered, which deal with special cases and therefore do not require the combination of the two designs. This review also discusses some of the scenarios where researchers take an integrated approach to the design of access and backbone networks. These configurations deal with special cases where access and backbone networks are a combination of the following configurations: ring, tree, star, path, or complete graph. For example: the access network can be a star and the backbone network a ring.

For the network we are considering for the Physical Internet, the access network may have the configuration of a star in special cases (if flows between π-gateways are not allowed) but the backbone network will often have an arbitrary form (no particular shape: a general graph [19]). Consequently, for our network design, we will not impose a particular shape for either the access network or the backbone network. [20] suggests that the access network can be considered as a two-level facility location problem with capacity consideration. The authors suggest that the backbone network can be considered as a network design problem with capacity constraints and survivability. Studying a network with existing backbone hubs, they optimized the two networks separately. [19] provides an example formulation of an arbitrary network with a single allocation based on the median p-hub location problem. This modeling can be used for access network design. [21] introduces a model based on the multi-commodity flow problem. The model considers the cost of establishing nodes and links between backbone hubs and access hubs. [22] similarly formulates a model based on the multi-commodity flow problem. The formulation considers the fixed costs of establishing nodes and links. This work focuses on a general structure in which the network of nodes is not topologically constrained.

To summarize, the Physical Internet network that we present is based on the design of access networks and backbone networks. In addition, our model does not impose any restrictions on the topology of the networks while meeting the needs of optimal routing of the goods. For the integrated design of the access and backbone networks, we will combine the median p-hub problem with the multi-commodity flow problem. This is the answer to the second research question.

3. MODEL FORMULATION

3.1. Description

In this paper, we want to build a Physical Internet network as presented in Figure 2. The network will be based on existing infrastructures that need to be upgraded to be compatible with the Physical Internet. At the same time, new infrastructures will be required for the deployment of the Physical Internet. Accordingly, the challenge is to identify the π-gateways and π-nodes to be included in the future network to minimize the total setup and transportation cost.

To locate the π-gateways, we used a formulation derived from the p-hub location problem. The location of π-nodes is modeled by a formulation derived from the multi-commodity flow problem. Thus, to localize both π-gateways and π-nodes, we combined the two models by defining the multi-commodities based on the flows that flow through the π-gateways.

Furthermore, we have added the fixed cost of setting up the π-gateways and π-nodes as well as the cost of setting up the links. Indeed, we consider that the implementation of the Physical Internet requires new logistic infrastructures and in particular warehouses, links (roads, railroads, etc.) and means (trucks, trains, handling equipment, etc.). These infrastructures will be different from those used in the current logistics networks. Depending on their condition and their compatibility with the Physical Internet, some of the current infrastructures can be upgraded. To complete the network, new infrastructure will be required. In both scenarios, costs will be incurred for the creation or the upgrade. On the other hand, the implementation of the Physical Internet will create new opportunities and will have economic, social, and environmental impacts. This will result in expected gains once the Physical Internet is in place. In our model, we have considered overall costs that include both expenses and gains. However, we have provided different costs for the setup of π-gateways and π-nodes since the operations to be performed and thus the facilities required are going to be different from one type to the other. We have also differentiated the costs of setting up the links. Indeed, we think that the links between the clients and the π-gateways would be conventional. They would cost less than the links between the π-gateways and the π-nodes, which would be more enhanced and automated. The links between the π-nodes would be even more advanced. Thus, possibly more expensive. To accommodate different scenarios, we have provided different costs for establishing the links.

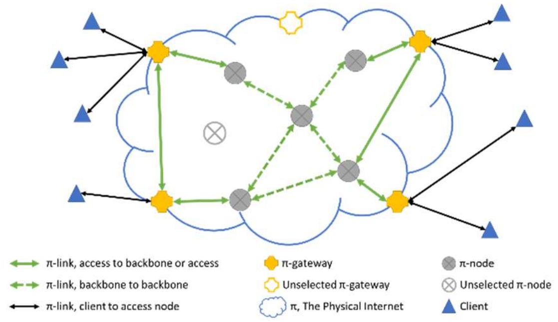

Figure 2. Our perception of the Physical Internet network

The variable costs of operating the facility (e.g., containerization costs, travel costs within the facility, etc.) are not explicitly modeled. This is because these are operational costs, whereas the model deals with a strategic issue. However, if they are known in advance, they can be included in the cost of using the links so that they can be varied according to the quantity transported.

3.2. Assumptions

For practical considerations, we consider the following assumptions:

- The flow of goods is done through the physical Internet. Direct flows between customers are not supported in this work.
- The cost of using a link is symmetric. The cost of moving from A to B is identical to the cost of moving from B to A.
- The cost of using links within the Physical Internet is optimal. There is no leveling effect that would make moving a quantity $q + \delta$ $(\forall \delta \geq 0)$ cheaper than moving the quantity q. Thus, the transportation cost can be proportional to the quantity transported.

3.3. Notations

3.3.1. Sets, indices, and work variables

G = (N, E), an undirected graph
W: the set of the network users (clients)
H_A: the set of access hubs (π-gateway)
H_B: the set of backbone hubs (π-node)
H: the set of all hubs (H = $H_A \cup H_B$)
N: the set of all nodes (N = W $\cup$ H)

L_A: the set of directed arcs connecting clients to access hubs

L_B: the set of directed arcs (π-links) connecting the access hubs to the backbone hubs, the backbone hubs to each other or the access hubs to each other.

L: the set of all directed arcs (L = $L_A \cup L_B$)

E_A: the set of edges (undirected arcs) connecting the clients to the access hub

E_B : the set of edges (undirected arcs) connecting the access hubs to the backbone hubs, the backbone hubs to each other or the access hubs to each other

E: the set of edges (undirected arcs) (E = $E_A \cup E_B$)

K: the set of commodities k that matches each demand r_k between an origin o(k) and a destination d(k). The origins and destinations are access hubs.

r_k: demand associated with the commodity k

F_i^A: fixed cost of setting up the access hub i

F_i^B: fixed cost of setting up the backbone hub i

G_{ui}^{WA}: fixed cost of setting up the edge (undirected arc) between client u and access hub i

G_{ij}^{AA}: fixed cost of setting up the edge (undirected arc) between the access hubs i and j

G_{ij}^{AB}: fixed cost of setting up the edge (undirected arc) between the access hub i and the backbone hub j

G_{ij}^{BB}: fixed cost of the setting up of the edge (undirected arc) between the backbone hubs i and j

a_{ij}: symmetric cost of moving a demand unit on the arc (i, j) in the access network

b_{ij}: symmetric cost of moving a demand unit on the arc (i, j) between access hubs; between access hubs and backbone hubs or between backbone hubs les hubs

b_{ij}^k: symmetric cost of moving the commodity k on the arc (i, j) in the backbone network

q_{uv} : demand to be moved between a client u and a client v

3.3.2. Parameters

α: number of access hubs assigned to a client

3.3.3. Decision variables

Z_i^A: {0, 1}, if the hub i is selected in the access network

Z_i^B: {0, 1}, if hub i is selected in the backbone network

Y_{ij}^A: {0, 1}, if the edge {i, j} is selected in the access network

Y_{ij}^B : {0, 1}, if the edge {i, j} is selected in the backbone network

X_{ij}^k : fraction of demand for commodity k moving on the arc (i, j) in the backbone network

3.4. Formulation

Using the above notations, our model can be formulated as follows:

$$Min\ (2) + (3) + (4) + (5) + (6) \qquad (1)$$

Where:

$$\sum_{u \in W} \sum_{\{u,i\} \in E_A} a_{ui} Y_{ui}^A \left(\sum_{v \in W} q_{uv} \right) \qquad (2)$$

$$\sum_{v \in W} \sum_{\{v,j\} \in E_A} a_{vj} Y_{vj}^A \left(\sum_{u \in W} q_{uv} \right) \qquad (3)$$

$$\sum_{i \in H_A} F_i^A Z_i^A + \sum_{i \in H_B} F_i^B Z_i^B \qquad (4)$$

$$\sum_{u \in W, i \in H_A} G_{ui}^{WA} Y_{ui}^A + \sum_{i \in H_A, j \in H_A} G_{ij}^{AA} Y_{ij}^B + \sum_{i \in H_A, j \in H_B} G_{ij}^{AB} Y_{ij}^B + \sum_{i \in H_B, j \in H_B} G_{ij}^{BB} Y_{ij}^B \qquad (5)$$

$$\sum_{k \in K} \sum_{(i,j) \in L_B} b_{ij}^k X_{ij}^k \qquad (6)$$

With:

$$K = \left\{ k = (o_k, d_k, r_k), \begin{cases} r_k = \sum_{u,v \in W} q_{uv} Y_{ui}^A Y_{vj}^A \\ o_k = i \\ d_k = j \end{cases}, i \in H_A, j (j \neq i) \in H_A \right\} \quad (7)$$

$$b_{ij}^k = b_{ij} \times r_k, (i,j) \in L_B, k \in K \quad (8)$$

Subject to constraints:

$$\sum_{i \in H_A} Y_{ui}^A = \alpha\,, \sum_{i \in H_A} Y_{iu}^A = \alpha\,, u \in W \quad (9)$$

$$\sum_{j \in H} X_{ij}^k - X_{ji}^k = \begin{cases} 1, i = o_k, i \in H_A, k \in K \\ -1, i = d_k, i \in H_A, k \in K \\ 0, i \in H_A \backslash \{o_k, d_k\}, k \in K \end{cases} \quad (10)$$

$$X_{ij}^k \leq Y_{ij}^B, \{i,j\} \in E_B, k \in K \quad (11)$$

$$X_{ji}^k \leq Y_{ij}^B, \{i,j\} \in E_B, k \in K \quad (12)$$

$$Y_{ui}^A \leq Z_i^A, Y_{iu}^A \leq Z_i^A, u \in W, i \in H_A \quad (13)$$

$$\sum_{i \in H} X_{ji}^k \leq Z_j^B, \sum_{i \in H} X_{ij}^k \leq Z_j^B, j \in H_B, k \in K \quad (14)$$

$$0 \leq X_{ij}^k \leq 1, (i,j) \in L_B, k \in K \quad (15)$$

$$0 \leq X_{ji}^k \leq 1, (i,j) \in L_B, k \in K \quad (16)$$

$$Z_i^A \in \{0,1\}, i \in H_A \quad (17)$$

$$Z_i^B \in \{0,1\}, i \in H_B \quad (18)$$

$$Y_{ij}^A \in \{0,1\}, \{i,j\} \in E_A \quad (19)$$

$$Y_{ij}^B \in \{0,1\}, \{i,j\} \in E_B \quad (20)$$

The objective function (1) aims to minimize the total cost of setup and transportation. This function can be broken down into five parts. (2) Corresponds to the cost of routing products between customers and access hubs. (3) Refers to the cost of transportation between access hubs and customers. In (4), the first term is the fixed cost of setting up the access hubs and the second term is the fixed cost of setting up the backbone hubs. These costs have been separated since the orders of magnitude of the access hub setup costs are different from the backbone hub setup costs. In (5), the first term is the cost of setting up links between clients and access hubs. The second term is the cost of setting up the links between the access hubs. The third term represents the cost of setting up the links between the access hubs and the backbone hubs. The fourth term is the cost of establishing links between backbone hubs. (6) represents the transportation cost between access hubs, between access hubs and backbone hubs, and between backbone hubs.

(7) defines the set of commodities k such that for every pair of access hubs i and j, a demand r_k is defined as the aggregation of demands that emanate from access hub i (called origin) towards access hub j (called destination). (8) defines the transportation cost b_{ij}^k of a commodity k on the arc (i, j) based on the demand r_k and the unit of transportation cost b_{ij}.

(9) is a constraint ensuring that a client is assigned to exactly α access hubs. (10) is a flow conservation constraint ensuring that flows into a hub are balanced with flows out of that hub. (11) and (12) allows a flow only on the selected arcs. (13) and (14) allow a flow only for the selected access hubs and backbone hubs respectively.

(15) and (16) indicate that the fractions of commodity-related demands are between 0 and 1. (17), (18), (19) and (20) state that the access hub and backbone hub selection variables are binary.

3.5. Special scenarios

The model allows a client to connect to α access hubs. This is convenient in last-mile management where the client can deliver or be delivered by multiple access hubs (case of restaurants, Dabbawala example [23]). In inter-city and inter-regional flows, the access hub handles a set of clients, and a client is served by one and only one access hub. In this case, $\alpha = 1$. To consider this aspect, the constraint (9) becomes:

$$\sum_{i \in H_A} Y_{ui}^A = 1, \sum_{i \in H_A} Y_{iu}^A = 1\,, u \in W \quad (9')$$

The model as defined allows flows between access hubs. In this case, goods can be routed between two access hubs without going through the backbone hubs. To exclude this kind of flow the following constraint (20) could be added:

$$b_{ij} = +\infty, b_{ji} = +\infty, i \in H_A, j \in H_A \qquad (20)$$

In the presented model, an access hub can be linked to several backbone hubs. To restrict the assignment of an access hub to a single backbone hub, the following constraint (21) could be added:

$$\sum_{j\in H_B} Y_{ij}^B = 1, \sum_{j\in H_B} Y_{ji}^B = 1\,, i \in H_A \qquad (21)$$

To summarize, we provide a mathematical model that combines the p-hub location problem with the multi-commodity flow problem. The model allows both π-gateways and π-nodes to be located by defining multi-commodities based on the flows that flow through the π-gateways. A detailed explanation is provided with the precision of special scenarios that allow the network configuration to be changed if necessary. This section answers the third research question.

4. DISCUSSION AND RESEARCH PERSPECTIVES

We have proposed answers to the research questions we raised. These answers open research opportunities that we will discuss in this section.

4.1. Characteristics of the network

We have designed a model that takes advantage of all cost optimization opportunities by selecting the appropriate routes. These opportunities are identified based on the transportation requests to be fulfilled. In the digital Internet, links are permanent. The transportation can be carried out as soon as an origin and a destination are determined. On the physical Internet, it is different. Transportation must be prepared and planned for each request. Therefore, it is necessary to know all the transport requests to be carried out through the network with their status. This makes it possible to choose the best route or to change it if a more attractive opportunity is available. The literature proposes some approaches such as the Internet of Things [24]–[26], Big Data analysis techniques [27], blockchain technology [28], [29], or data management [30]. These approaches are not yet mature. The Physical Internet still needs a central platform that collects all data from the network.

The physical Internet network will necessarily have to coexist with existing logistic networks. Some publications address the subject from a conceptual point of view. [31] starts from the analogy with the Digital Internet to decompose logistics networks into autonomous systems. In the framework of the Physical Internet, these autonomous systems interconnect through π-hubs that are presented as the equivalent of routers in the Digital Internet. The authors briefly discuss interconnection with heterogeneous networks. But this heterogeneity comes from different transportation modes, not from the fact the logistics networks operate differently. [32], [33] consider interconnection from another point of view. They propose an equivalent of the OSI (Open System Interconnection) model and the TCP/IP (Transmission Control Protocol/Internet Protocol) model for the Physical Internet. The model creates an abstraction that helps design interconnected networks. But these networks must have the same underlying protocols. The classical logistic networks and the Physical Internet are very different. These differences are found in the identification data, the containerization package, the types of transport means used, etc. We believe that the use of π-gateways is the key. However, the details of the interconnection between the two networks still need to be defined.

4.2. Network architecture

We provide an architecture based on an access network and a backbone network. This architecture could contribute to the development and transposition of concepts and business models from the Digital Internet to the Physical Internet. We can suggest two concepts to be transported: routing and supervision.

When the network is established, it is necessary to implement a set of protocols for routing, management, and performance monitoring of the network. Regarding routing, [34] considers a shortest path problem solved with the “A* euristic”. The proposed simulation takes into account the cost, delivery time and CO2 emissions but does not consider the network state. [35] proposes to transpose the Border Gateway Protocol to the Physical Internet to allow switching to neighboring π-hubs in case of delay or congestion. Both works propose simulations. With the backbone and access network approach that we propose, a mathematical model could be developed to adopt one of the most used protocols in the Digital Internet called Open Shortest Path First [20] for the Physical Internet.

To monitor the state of the equipment in a digital network, Simple Network Management Protocol (SNMP) has been implemented. It is a simple protocol by which the management information of a network element can be inspected or modified by remote users [36]. This concept could be transposed to the Physical Internet to collect and share information about the state of the different network components through connected devices. To this end, the network we propose could be used as a concrete framework for testing and exploring these protocols.

4.3. Mathematical model

The model we propose presents a first building block for the implementation of a network for the Physical Internet based on the Digital Internet networks. This model can be improved through:

- Considering capacity for π-nodes, π-gateways, and different links. Indeed, the location models often include a version that considers the capacity. For our case, we primarily want to estimate the orders of magnitude of the capacities of π-nodes, π-gateways, and links to assess the strategic feasibility of the concept. Thus, reformulating the model with a capacitated vision is a potential direction of progress.
- Taking into account the features of the π-node types (π-hub, π-transit, π-bridge, π-switch, π-store) of the Physical Internet [2] and identifying the appropriate types to deploy. For the needs of mode switching (maritime, road, rail, etc.), a π-switch could be used for monomodal and π-bridge for multimodal. However, if the π-container is multi-destination, it should be handled in a π-hub. Ideally, a flow classification could be implemented to allow the model to identify and locate the appropriate π-node type for each flow.
- Considering social sustainability and in especially allowing drivers to return home by the end of the day. The approaches [4], [37], [38] take this dimension into account through additional costs. Of course, these models select optimal solutions, but they still allow for overrun situations. Ideally, the model should allow for the creation of intermediate nodes by cutting out long paths to ensure this constraint in a structural way.
- Exploring the design of multilayer networks [39]–[42] to simplify the modeling of constraints related to the management of certain types of transported content (people, dry, positive, negative, dangerous). This design allows complex problems to be modeled by separating the decision variables into several layers and defining bonding constraints between these different layers.

4.4. Enabled research opportunities

Through an example, we propose new research opportunities unlocked by our proposed architecture and inspired by the Digital Internet. These opportunities are based on the principle of dynamic resource allocation and could help develop new business models in the context of the Physical Internet.

Pre-allocation and dynamic allocation are two fundamental and competing approaches in communication [14]. This also applies to logistics. Accordingly, by outsourcing transportation and warehouse management operations, companies change from pre-allocation of resources to dynamic allocation. Following this philosophy, the Physical Internet is a progress. To better illustrate the concept, we give the following example. Instead of investing in a truck that is not used all the time, a truck is rented for a trip. However, the rented truck may not be completely full, and the price includes the empty return. Thanks to the Physical Internet and the network we provide, the price to be paid should correspond only to the space used in the truck. Indeed, an appropriate truck will deliver the π-gateway assigned to the sender. On the return trip, the truck will pick up the goods for the sender from the assigned π-gateway. At the π-gateway, the goods are bundled and then sent to the nearest π-node in the path to the recipient. Then, the π-nodes relay the shipment to the π-node closest to the π-gateway assigned to the recipient where it will be unbundled. Finally, an appropriate truck will pick up the goods at the assigned π-gateway to deliver them to the recipient. This truck could previously deliver a commodity that the recipient would like to send. This example is also valid for storage. The network we propose not only allows dynamic allocation of storage based on need, but it unlocks the possibility of distributing storage across multiple π-nodes. This would bring the products closer to the consumers without any additional cost. Such a configuration is economically hard to achieve with proprietary networks where each company must own or lease each warehouse it uses.

The previous example also illustrates all the business opportunities that are available through our proposed network. The truck delivering the π-gateway could be provided by a Physical Internet Service Provider. The π-gateway and π-nodes can be managed by independent operators offering services for containerization, consolidation, deconsolidation, storage, etc. The backbone links can be built and maintained by specialized companies. So can the transportation means used for transportation. We could push the exercise even further by considering a complete virtualization of the logistics services with economic models such as "pay as you go", hourly billing for storage or managing one's own virtual logistics platform (which can be physically distributed over several logistics centers). Not to mention the gains that clients of the Physical Internet could make by refocusing on their core business.

5. CONCLUSION

Technological progress and the continuous evolution of consumer needs challenge supply chains to constantly adapt and improve. Supply chains need to meet these challenges in a sustainable way and without additional costs.

In this paper, we support the Physical Internet as a framework for the development of future logistics networks. Respectively, we have addressed the design of a network for the implementation of the Physical Internet. To guide our research, we formulated three questions: (1) What are the characteristics of the proposed Physical Internet network? (2) What is the configuration of this network? (3) What is the mathematical model that respects this configuration and preserves the requested features?

To answer the first question, the network must meet two important characteristics. On the one hand, it must allow taking advantage of all optimization opportunities. For example, the model must allow any number of intermediate nodes to be traversed between each origin/destination pair. On the other hand, it must allow interconnecting with existing logistics networks through the π-gateways that are a key part of the future network.

The answer to the second question comes from the analysis of location approaches in complex communication networks. We selected the approach that combines an access network and a backbone network without the restriction of the networks' topology. Thus, we combined the median p-hub problem with the multi-commodity flow problem.

Finally, we answered the third question with a mathematical model that represents the Physical Internet network as a graph. The model considers the setup costs of nodes and links. To be more specific, the cost of setting up the access hubs is distinguished from the cost of setting up the backbone hubs. The costs of setting up links are also separated: the cost of setting up links between clients and access hubs; the cost of setting up links between access hubs; the cost of setting up links between access hubs and backbone hubs; and the cost of setting up links between backbone hubs. For transportation, the model considers different costs: transportation cost between customers and access hubs within the access network; and transportation cost within the backbone network. Through the additional parameters and constraints presented, the model can adapt by changing the network configuration.

The main contribution of this work is that it is the first to introduce an access network and backbone concept for the design of the Physical Internet. Our approach is different from the current literature on location problems for the Physical Internet. We propose a model that does not enforce any restrictions on the network topology to fully benefit from all cost optimization opportunities. The number of intermediate nodes is completely variable and the decomposition into multiple echelons is no longer necessary. We propose to replace the underlying reference to logistics chains with an interconnected network between all actors. This network naturally supports all flows: raw material, direct logistics, reverse logistics, etc. By joining our access network and backbone network architecture to the π-gateways, the interconnection with current logistics networks is natively supported. This combination also allows for a progressive deployment of the Physical Internet seamlessly to users.

This work comes in response to the limited perception of the Physical Internet network in the literature. We believe that this contribution could improve this perception and thus open new research perspectives. Indeed, the network perception we propose could allow applying the knowledge established in the Digital Internet more easily to the Physical Internet.

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