REPUBLIQUE ALGERIENNE DEMOCRATIQUE ET POPULAIRE
الجمهورية الجزائرية الديمقراطية الشعبية

MINISTRY OF HIGHER EDUCATION AND SCIENTIFIC RESEARCH

HIGHER SCHOOL IN APPLIED SCIENCES
--T L E M C E N--

وزارة التعليم العالي والبحث العلمي

المدرسة العليا في العلوم التطبيقية
-تلمسان-

Final degree project

For obtaining the Master Diploma

Field: Industrial engineering
Major: Industrial Management and logistics

Presented by:
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Subject

Container flow optimization in a Physical Internet context

Publicly defended, on 03/07/2024, in front of the jury composed of:

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School year: 2023 /2024

Gratitude

I would like to express my sincere gratitude and deep appreciation to:

My advisor, supervisor and program director, Mr. Fouad MALIKI, for being the epitome of an exemplary teacher, guiding not only me but all of us throughout these four enjoyable and incredible years of study. I also extend my heartfelt thanks to my co-advisor, Mr. Tarik CHARGUI, for providing me with this opportunity and enriching my knowledge in the field. Their valuable advice and guidance throughout the period of completing this modest work have been indispensable, and I am truly grateful for their interest in my work.

I would also like to extend my gratitude to Mr. Abdelghani BEKRAR for his invaluable assistance and help, and for all the members of LAMIH during my period of internship.

I would also like to thank the members of my jury for the great honor they bestow upon me by agreeing to evaluate this modest work.

My thanks extend to all my teachers who have contributed significantly to the quality of my education. Finally, I express my gratitude to everyone who has participated, directly or indirectly, in the realization of this thesis.

Acknowledgement

To my beloved parents,

For your unconditional and unlimited love, unwavering support, and endless sacrifices. This project is the result of your constant encouragement and unwavering faith in me. I dedicate this work to you with deep gratitude and immense love.

To the best sisters in the world, Habiba, Meriem, Bouchra, and my twiny Sara,
For your unwavering support, encouragement, and understanding throughout this journey. Your love and belief in me have been a constant source of strength and inspiration. This project is a testament to the bond we share and the invaluable role you play in my life.Thank you for always being there, for your words of wisdom, and for cheering me on every step of the way. This achievement is as much yours as it is mine.

To my best friend Ghizlène, your friendship is a treasure I cherish deeply. Thank you for being my rock, my confidant, and my constant source of inspiration. To the best roommate and internship colleague Niama, sharing this journey with you has been an incredible blessing.I am grateful for our bond and the memories we've created together. To all my friends Feriel.S, Razane.B, Mannel.A, Manèl.S, Souhila.F, Rym.G, Safia.Y Aymen.K, Mohieddine.T, Salah.S and Azzedine.B, Thank you for your constant support and encouragement throughout this journey. Your friendship has given me strength and motivation, and I am so grateful to have you in my life.Your belief in me, our shared laughter, and your advice have made this journey much easier and more enjoyable.

Contents

Abstract

This thesis explores the Physical Internet (PI) as a transformative approach to logistics and supply chain management. It highlights the inefficiencies of traditional systems and introduces the PI's concepts, including modular containers and dynamic routing. The study covers the design requirements for PI-containers and addresses the vehicle routing problem within the PI context, offering both single-period and multi-period models using modular PI-containers and PI-boxes.

Keywords: Physical Internet, VRP, PI-containers, PI-boxes, Multi-objective optimization, Cplex, Gurobi.

Résumé

Cette thèse explore l'Internet Physique (PI) comme une approche transformative pour la logistique et la gestion de la chaîne d'approvisionnement. Elle met en évidence les inefficacités des systèmes traditionnels et présente les concepts du PI, y compris les conteneurs modulaires et le routage dynamique. L'étude couvre les exigences de conception des conteneurs PI et aborde le problème de routage des véhicules dans le contexte du PI, en proposant des modèles à période unique et à périodes multiples en utilisant des PI-conteneurs et des PI-box modulaires.

Mots clés: Internet physique, VRP, PI- conteneurs, PI-boxes, Optimisation multi objectives Cplex, Gurobi.

تلخيص

تستكشف هذه الأطروحة تحسين الخدمات اللوجستية في إطار مفهوم الإنترنت المادي. وهو يركز على مشكلة التوجيه والموقع (LRP) . نموذج في البداية، تتناول الأطروحة LRP ذات هدف واحد يهدف إلى تقليل تكاليف النقل باستخدام منهجيات الحلول المختلفة، بما في ذلك الحلول الكلاسيكية مثل CPLEX والأساليب الماورائية مثل محاكاة التلدين والاستراتيجيات الهجينة. وبعد ذلك، يمتد الأمر إلى التحسين متعدد الأهداف الذي يأخذ أيضًا في الاعتبار العوامل البيئية مثل انبعاثات ثاني أكسيد الكربون. تم حل المشكلة متعددة الأهداف باستخدام خوارزمية Gurobi و AMOSA . وأظهرت النتائج فعالية الأساليب المقترحة لتحقيق الكفاءة الاقتصادية والاستدامة البيئية في العمليات اللوجستية.

الكلمات المفتاحية: الإنترنت المادي، VRP ، حاويات PI ، صناديق PI ، تحسين Cplex متعدد الأهداف، Gurobi

General Introduction

In today's rapidly evolving landscape of global commerce and logistics, achieving efficiency, sustainability, and resilience has become of prime importance. Traditional supply chain models, although once effective, are now confronted with significant challenges that span economic, environmental, and societal aspects. Addressing these challenges necessitates innovative solutions, and the Physical Internet (PI) emerges as a promising paradigm. Inspired by the principles of the Digital Internet, the Physical Internet envisions a seamless and interconnected network for the movement of physical goods. By adopting key concepts such as modular and standardized containers and dynamic routing algorithms, the Physical Internet aims to revolutionize how goods are transported, stored, and distributed. This thesis explores the transition from traditional logistics to the Physical Internet, delving into its core principles and potential to transform supply chain operations into more efficient, cost-effective, and environmentally friendly systems.

In the first chapter comprehensive overview of the current state of logistics and supply chains was provided, identifying inefficiencies and sustainability issues. It introduces the concept of the Physical Internet, detailing its foundational principles and comparing it to the Digital Internet. The chapter also includes a review of recent literature and research on the Physical Internet, offering insights into its development and implementation.

The second chapter focuses on the design and the requirements of PI-containers, which are key components of the Physical Internet. It discusses the physical and informational requirements for these containers, ensuring they are robust, interoperable, and capable of seamless integration within the logistics network. The chapter also explores routing protocols for PI-containers, drawing parallels with the Border Gateway Protocol used in digital internet networks.

The last chapter addresses the vehicle Routing Problem (VRP) within the context of the Physical Internet. It presents a single-period model, outlining the problem description, assumptions, and mathematical formulation. The resolution approach and application of the model are discussed, along with the data used and the results obtained. The chapter further extends the analysis to a multi-period model, providing a more comprehensive understanding of the VRP's implications for the Physical Internet. The main idea of this chapter was to introduce another principle of the physical internet which is the utilisation of PI-containers.

Chapter 1

Physical Internet concepts : State of the art

Introduction

In today's rapidly changing world of global commerce and logistics, the quest for efficiency, sustainability, and resilience stands as a top priority. Traditional supply chain models, while effective in their time, are increasingly facing challenges. These challenges manifest in various aspects of supply chain operations: in an economic, environmental and societal aspect.

Recognizing the need for transformation and changing, the concept of the Physical Internet emerges as a promising solution to overcome the limitations of classical supply chains. At its core, the Physical Internet is a new paradigm drawing inspiration from the principles of the Digital Internet to create a seamless and interconnected network to the movement of physical good easier.

Key concepts of the Physical Internet, such as modular and standardized containers and dynamic routing algorithms, are introduced as fundamental building blocks of this transformative vision. By adopting these principles, the Physical Internet aims to change and revolutionize the way goods are transported, stored, and distributed.

In this chapter, we explored in the first place the transition from traditional logistics to the innovative concept of the Physical Internet. Then, we delved into the concept of the Physical Internet, exploring its core principles and comparing it with the Digital Internet to enhance comprehension of its potential. Additionally, we touched upon ALICE, a collaborative platform driving logistics innovation. Finally, we wrapped up with a state-of-the-art overview, discussing recent articles and research pertaining to the Physical Internet.

1.1 Logistics and supply chain

1.1.1 Logistics definition

"Logistics" was initially a military-based term used in reference to how military personnel obtained, stored, and moved equipment and supplies. The term is now used widely in the business sector, particularly by companies in the manufacturing sectors, to refer to how resources are handled and moved along the supply chain. It refers to the overall

process of managing how resources are acquired, stored, and transported to their final destination.[Kenton, 2024].
In the pure context of industry,[Ballou et al., 1973] defined logistics as "the process responsible for planning, implementing, and controlling the flow and storage of materials, goods, services, and information from origin to the consuming point."
[?] proposed another definition for logistics: " the flow of material,information, and money between consumers and suppliers"

1.1.2 Supply chain definition

A supply chain is the network of all the individuals, organizations, resources, activities and technology involved in the creation, distribution ans sale of a product. A supply chain encompasses everything from the delivery of raw materials from the supplier to the manufacturer through to its eventual delivery to the costumer and the end user.[Lutkevich,]
[Christopher, 2022] also defined supply chain as "the network of organizations that are involved, through upstream and downstream linkages, in the different processes and activities that produce value in the form of products and services delivered to the ultimate consumer".

1.1.3 Supply chain network

Supply chain network design means figuring out the best way to set up the supply chain so we can see how much it costs and how long it takes to get the products to market with the resources and places we have. In this process, there are many factors and models involved. This includes the strategic placement of distribution centers that are served from manufacturers, retailers and possible routes to serve those stores.[Forrest, 2024]
Classical supply chain network has actually a hierarchical distribution form, from suppliers to manufacturers, to warehouses to distribution centers and finally to retailers.

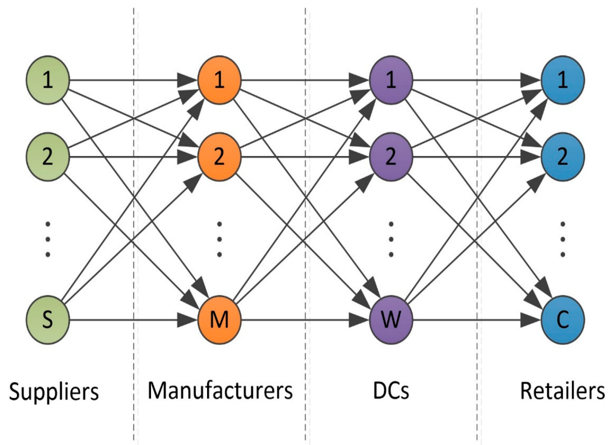

Figure 1.1: Supply chain network

1.1.4 logistics management and supply chain management

According[Tien et al., 2019] to Supply chain management is the seamless coordination of activities from customer orders to cash flows, linking distributors, inventory, manufacturers, and suppliers.SCM operates on the principle that almost every product reaching the market is the outcome of collaboration among multiple organizations forming a supply chain.

Logistics management refers to the process of strategically planning, executing, and managing smoothly the flow and the storage of goods, services, and associated information from their origin to the end-user, ensuring they meet customer requirements and expectations efficiently and effectively.
The author supposed that Logistics management is a part of supply chain management, which covers all the logistics activities of firms, their partners, and the combined benefits of these activities, among other components. The main idea is that supply chain is composed of the different activities of logistics and he explained that in the figure below 1.2

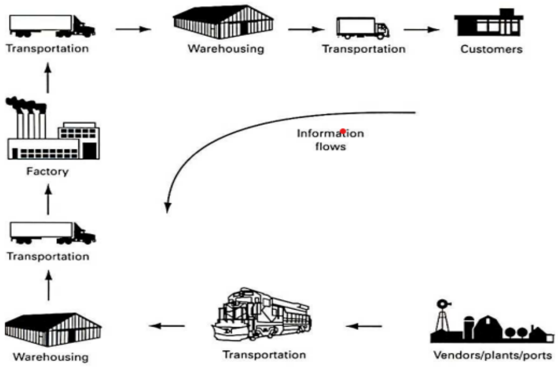

Figure 1.2: logistics and supply chain

1.1.5 Efficiency and sustainability of the current logistics system

According to [Montreuil, 2011] logistics is efficient when it satisfies the demand and the needs for moving, storing, supplying and using physical goods while minimizing the utilization of economical, environmental and societal resources. It is sustainable when it upholds high economical, environmental and societal performance over the time while facing and confronting risks in a dynamic context.

Today, the world is facing an inefficiency and unsustainability of the current logistic system due to its limitations. These limitations are seen from different aspects [Montreuil, 2011]:

- **The economic aspect :**Represented by different logistics costs that can be divided into five main components depending on the point at which the product is situated within the supply chain :Warehousing costs(Incoming goods),Warehousing costs(Storage),Fulfillment costs(Pick pack),Shipping costs(Delivery) and finally other logistics Costs(Returns). Logistics costs have increased by approximately 5% since 2010, mainly due to the growing intricacy of e-commerce logistics, these costs currently represent 12 to 20 percent of e-commerce revenues.[cos,]

  In 2021, the total transportation logistics costs in the United States reached approximately $1.2 trillion. Specifically, transportation costs for motor carriers (including full truckload, less-than-truckload, and private or dedicated) accounted for $830.5 billion[Placek, 2024].

- **The environmental aspect :** Represented by energy consumption, pollution, material waste and greenhouse gas emissions. Actually freight transportation accounts

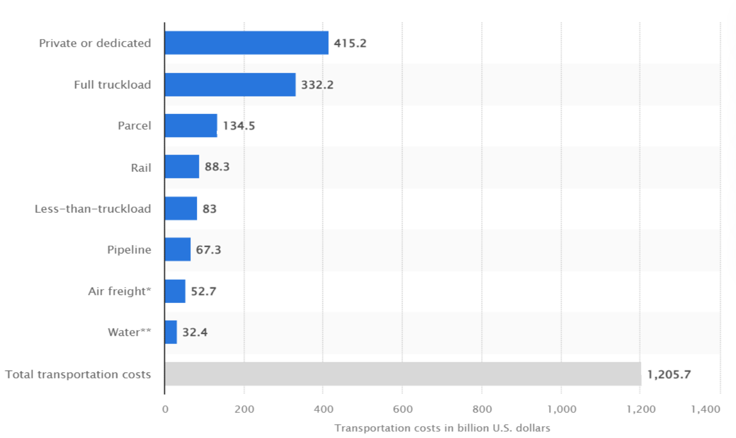

Figure 1.3: Transportation costs by type in the united stats in 2021

for 14% of France's gas emissions, showing a yearly growth rate of around 23% between 1990 and 2006.
In 2022, global transportation-related emissions totaled 7.97 billion metric tons of carbon dioxide (GtCO2), marking a 4.7 percent increase compared to 2021 levels. These emissions have surged over the past 50 years, rising from just 2.8 GtCO2 in 1970. Actually, between 1990 and 2022, global transportation emissions increased by more than 70 percent. These results and statistics were provided by Statista website [Tiseo, 2024], and the statistics are presented in the figure below 1.4

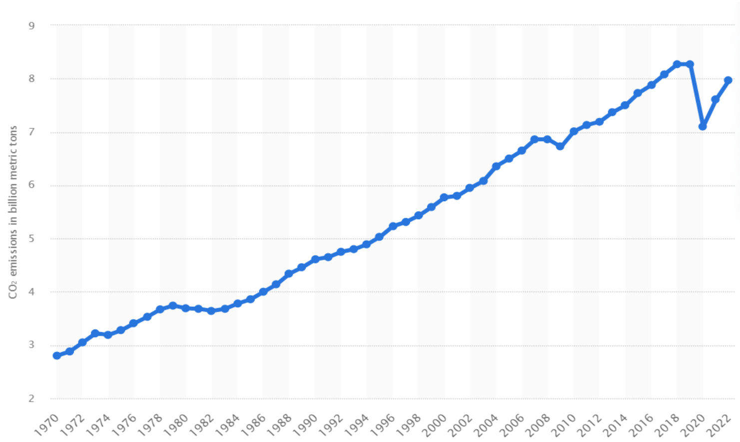

Figure 1.4: Global transportation sector CO emissions 1970-2022

- **The societal aspect :** Represented by drivers work conditions,the security of our logistics system, job opportunity creation, regional development promotion and safety concern[Peng et al., 2021].

  Some studies showed that prevalence of minor psychiatric disorders, depression, and anxiety among truck drivers is in the range of 6.1%, 13.6%, and 7.9%, respectively and approximately, 8,000 truck accidents each year are attributed to truck driver fatigue [Lindner, 2024].
  In 2020 in the USA, Texas stands out as being the most dangerous state for truck accidents with 568 accident per year.1.5 showed how Texas and the other high-risk states fare when it comes to fatal truck accidents in 2020. [Adam Ramirez, 2024]

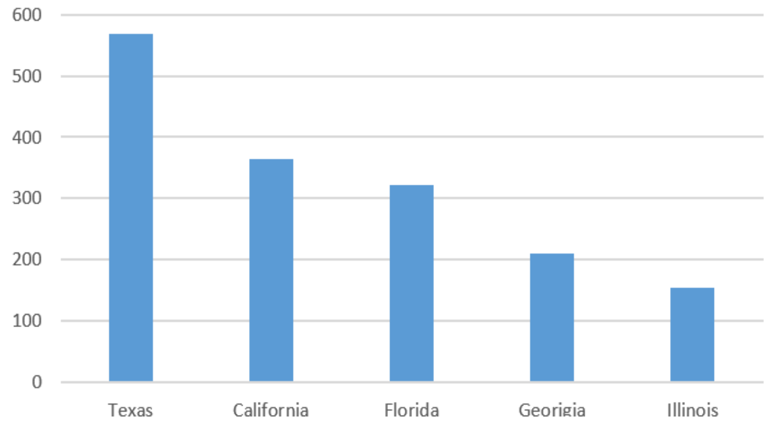

Figure 1.5: truck accidents in USA on 2020

1.1.6 Unsustainability symptoms

[Montreuil, 2011] summarized the symptoms of economic, environmental and societal unsustainability in 13 main principles:

- **Low rate of vehicle loading** : because of the half-emptiness of trucks, wagons and containers at the departure and they aren't fully loaded to their capacity. in 2004 in Germany, a study done with 50 German transport providers, obtained an average load capacity of 60% by volume and 44% by weight for all categories of vehicles studied.[**?**]

Figure 1.6: Truck's emptiness rate

- **Empty travel** :Most of the time vehicles and containers returns empty. This occurs when trucks or vehicles travel back to their origin empty after delivering goods. Factors contributing to empty travel include uneven demand, logistical constraints, and the need for fleet flexibility.

- **Truckers work conditions** : Because of the high demand of truck drivers coupled with the essential role they play in transporting goods, means they often face rigorous schedules, tight deadlines and long working hours, so that's why they are most of the time away of their homes,families and social life.

- **Unneeded storing and unavailability of products when and where needed** : Products are often stored in warehouses or distribution centers where they may sit idle for extended periods, especially if there isn't immediate demand in that location. As a result, even though products may be in stock somewhere, they might not be easily accessible to meet urgent requirements.

- **Production and storage facilities are poorly used** : For example in the case of seasonal products, production and storage facilities may face unique challenges in utilization. However, during off-peak seasons, facilities may operate at reduced capacity or even sit idle. Similarly, storage facilities may experience fluctuations in occupancy, with increased demand for storage space during peak seasons and decreased demand during off-peak periods.

- **So many products are never sold, never used**: Many products end up never being sold or used, contributing to waste and inefficiency in production and consumption. This is well-known in clothing,food and cars industry.

- **Products do not reach those who need them the most** : A significant challenge in global trade is ensuring that essential products reach those who need them most, particularly in non-developed countries and disaster zones in where logistics infrastructures and services decrease significantly.

- **Fast and reliable intermodal transport is still a dream or a joke** : The realization of fast and reliable intermodal transport remains a distant goal rather than a reality for many regions because of badly designed interfaces,poor synchronization and risky intermodal routes.

- **Flexible City logistics is hard to reach** : Transporting goods in cities is a logistical nightmare due to congestion, limited space, and complex infrastructure. Delivery vehicles struggle with traffic, narrow streets, and parking issues, while last-mile delivery presents additional challenge.

- **Products unnecessarily move, crisscrossing the world**: Products frequently take unnecessary trips around the world, moving inefficiently due to disjointed supply chains and poor coordination.

- **Networks are neither secure nor robust** : Because many businesses concentrate their operations in only a few centralized facilities, their logistics networks and supply chains become vulnerable to terrorism and natural disasters.

- Smart automation and technology are hard to justify

- **Innovation is strangled** : Innovation faces obstacles, particularly due to the absence of universal standards and protocols, as well as a lack of transparency and open infrastructure..

To address these challenges, a novel concept known as **the Physical Internet** has emerged. The Physical Internet paradigm is a new concept that aims to change how goods are transported, with a main objective to optimize the efficiency and sustainability of global logistics networks. At its core, the Physical Internet draws inspiration from the digital internet, envisioning a seamlessly interconnected and standardized physical network for the movement of goods.

1.2 Physical internet

1.2.1 Physical Internet definition and main concepts

The Physical Internet (PI,π) concept has been recently introduced as a response to the Global Logistics Sustainability Grand Challenge [Montreuil, 2011]. It is defined as an open global logistics system founded on physical, digital and operational interconnectivity through encapsulation, interfaces and protocols aiming to change the way physical objects are moved, handled, stored and transported based on the structure and the principles of Digital internet. [Montreuil et al., 2013]. The main objective of PI is to move from a closed,independent logistics network into an open,dependant logistics network.

The Physical Internet changes how goods are moved and stored by creating a super-connected logistics system. Everything is packed in smart, standardized PI-containers, from small cases to large cargo containers. These containers are tracked and managed in real-time as they move through logistics centers. Handling systems and vehicles are designed to work smoothly with these containers, making the whole process more efficient.

Physical Internet concept is based on three key elements : PI-containers, PI-movers and PI-nodes. [Montreuil et al., 2010]

- **PI-containers:** Modular containers with standardized dimensions based on the concept of encapsulation. They are easy to manage, store, transport,interlock, load and unload. They are also smart to allow their proper identification and routing, recyclable and eco-friendly. According to [Sallez et al., 2015] PI-containers can be classified into three main categories : transport, handling and packaging containers.
  - Transport containers or T-containers :They are large entities transported by the different types of vehicles (trucks, trains, ships. . .) on the PI networks. They're made to be easy to carry, tough enough for harsh conditions, and stackable like regular shipping containers used in maritime transport. They can contain directly physical objects or containers of smaller size. They have all the same width and high (2.4m*2.4m) but with different lenghts(1.2, 2.4, 3.6, 4.8, 6 or 12 m).
  - Handling containers or H-containers :They are designed to be handled by PI-handlers (conveying systems, lifts. . .) and to resist handling conditions in the PI-nodes.They can also contain physical objects or containers of smaller size.The standard maximum external size of an H-container enables it to fit inside a T-container with external sides measuring 1.2 meters. Smaller modular dimensions along the X, Y, and Z axes range from approximately 50%, 40%, 30%, 20%, down to 10% of this maximum size.
  - Packaging containers or P-containers :They are the smallest type of PI-containers and they are used to contain directly the physical goods. They're made to easily fit inside H-containers, being thin and lightweight for effortless handling. They protect the product and can be stacked when required.Essentially they are designed to replace custom packaging.

Figure 1.7: PI-containers

- **PI-movers:** used to move the PI-containers .PI-movers can temporarily store π-containers, even if that's not their main job.The main types of π-movers are π-transporters,π-conveyors and π-handlers.
  - π**-transporters** are designed to ensure a safe and efficient transportation of PI-containers. π-transporters includes π vehicles (π-trucks, π-locomotives, π-boats, πplanes, π-lifts and π-robots.) that are self-propelled and π carries that have to be pushed or pulled (π-trailers, π-carts, π-barges and π-wagons) that have to be pushed or pulled.

Figure 1.8: PI-lift-truck [Montreuil et al., 2015]

- π**-conveyors** are designed specifically to continuously move π-containers along predefined routes, without the need for π-vehicles and π-carriers. π-conveyors defers from simple conveyors by the fact that π-conveyors doesn't use any belts or rollers to support goods during their continuous flow, theπ-containers are just attach to the π-conveyor gears and get pulled along.

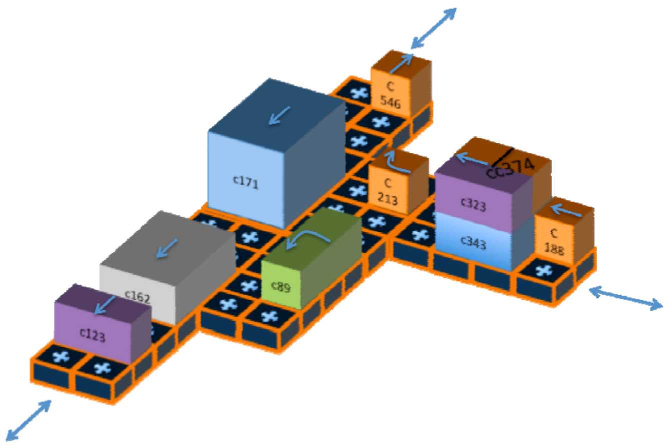

Figure 1.9: PI-conveyor [Montreuil et al., 2015]

- **PI-nodes:** Locations for receiving, sorting, storing and transferring PI-containers. They are equipped with automated and sophisticated handling systems. They are interconnected to the logistics activities.The PI-nodes include : PI-transits, PI-bridges, PI-switches, PI-hubs,PI-sorters, PI-composers, PI-stores and PI-geteways.
  - **PI-transits** ensure the transfer of π-carriers from their inbound π-vehicles to their outbound π-vehicles.
  - **PI-transits** and PI-bridges enable the unimodal transfer of π-containers from an incoming π-mover to an outgoing π-mover.
  - **PI-hubs** having for mission to enable the transfer of π-containers from incoming π-movers to outgoing π-movers. There is many types of PI-Hub : Road-Road PI-Hubs, Rail-Road PI-Hubs, Road-Rail PI-Hubs... 1.10
  - **PI-sorter** is designed to receive π-containers from one or multiple entry points and having to sort them so as to ship each of them from a specified exit point.
  - **PI-composers** main mission is to construct composite π-containers from specified sets of π-containers according to a specific 3D layout.

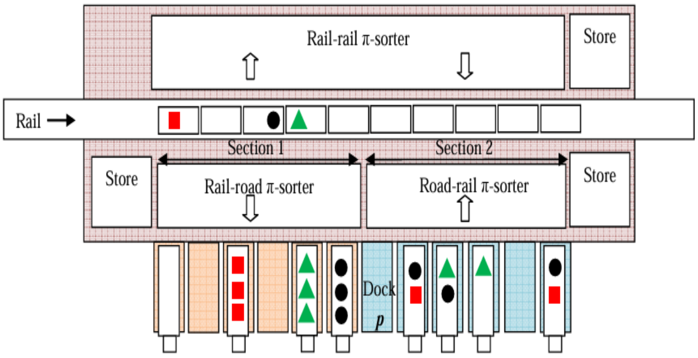

Figure 1.10: Rail-road PI-hub

- **PI-stores** ensure and facilitate the storage of π-containers for its clients within mutually agreed-upon time windows.Essential factors for their success include both the capacity and speed for receiving π-containers and dispatching them. PI-stores have two main functionalities : stacking and snapping of π-containers and they are mentioned in figure1.11

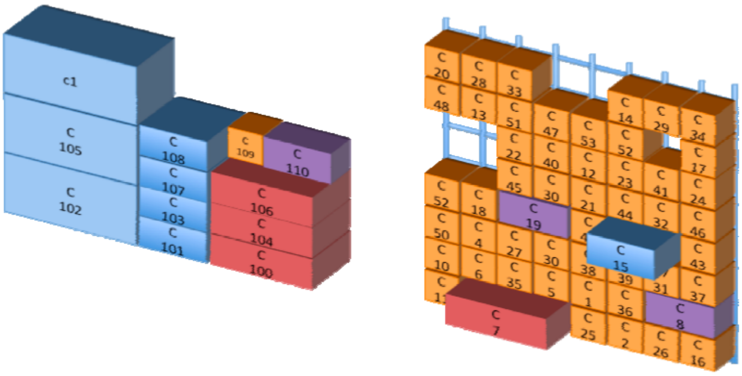

Figure 1.11: stacking and snapping functionalities in a PI-store [Montreuil et al., 2015]

- **PI-geteways** either receive PI-containers from PI-network and release them to a private network, or receive PI-containers from a private network and give them an access to PI-network.

In summary, PI-nodes are the connection and exchange points in our Physical internet network, PI-movers facilitate the transportation of PI-containers between the different PI-nodes. Together, these elements enable the efficient, flexible, and sustainable movement of goods within the global network.

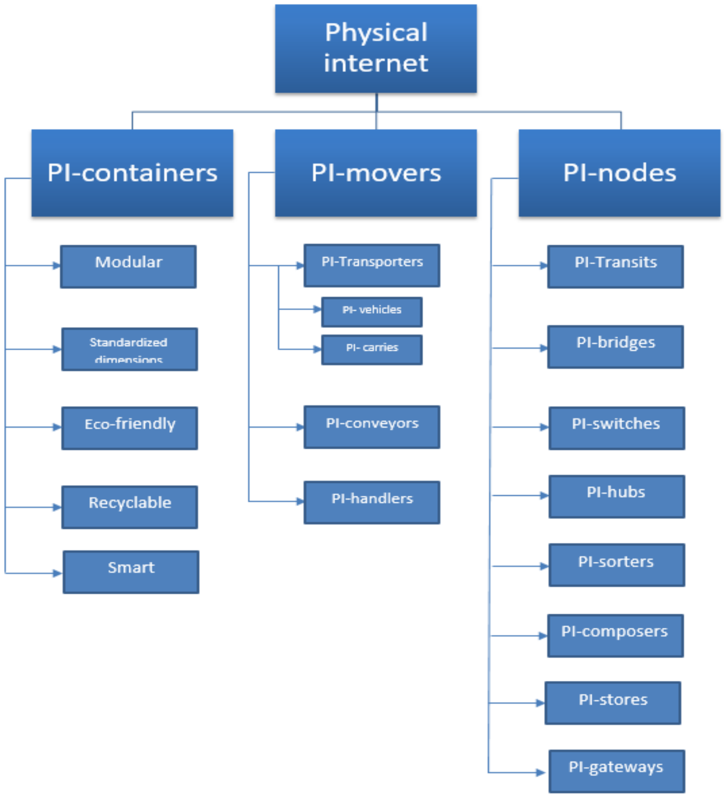

Figure 1.12: Key elements of Physical Internet

1.2.2 From the Digital Internet to the Physical Internet

According to [Montreuil et al., 2012] Physical Internet aims to establish a global interconnectivity among logistics networks by adopting standardized containers, PI-interfaces and protocols to improve the supply chain sustainability and efficiency. PI aims to organize the transportation of physical goods in a manner similar to the way in which packets are moved in Digital Internet using a set of standardized protocols.

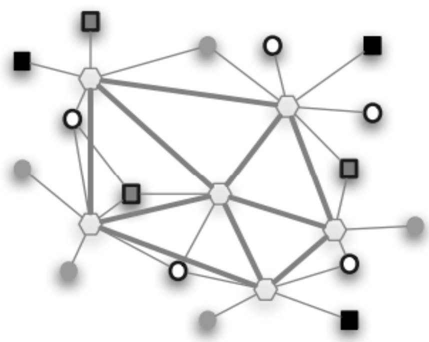

Figure 1.13: PI inter-connectivity

Digital Internet

[Dong and Franklin, 2021]The DI is a sophisticated engineering system that interlinks billions of devices globally, theoretically enabling each device to communicate with every other. Internet users, whether governmental, commercial, or private entities, utilize terminal devices like computers or smartphones. These users input data into the DI in the form of digital information, which is encapsulated into data packets and transmitted through a network of communication links. The term "router" is used as a general term to cover the functions of classic routers, switches and hubs.

Internet protocols

Internet protocols have been introduced to standardize and organize its operationalization. A protocol defines the format of the packets of digital information exchanged between peers in the DI, how hosts should be addressed, as well as the actions taken in the transmission of the packets across the DI. Among the most well-known protocols we found the TCP/IP and OSI(Open Systems Interconnection model) protocols.

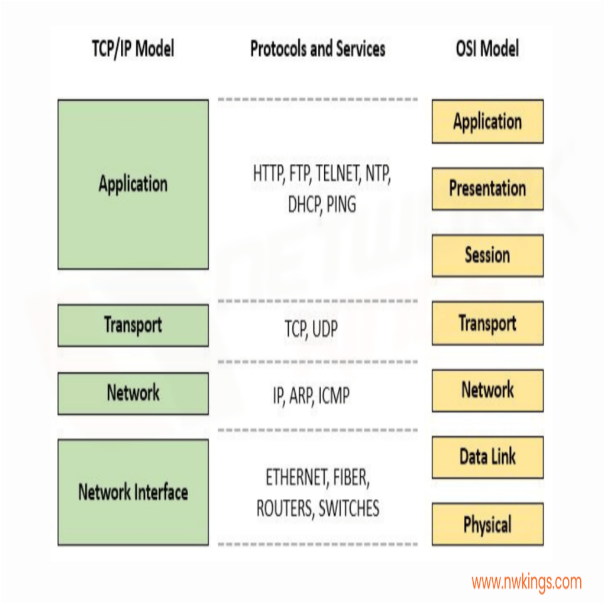

Figure 1.14: Internet protocols

OSI and OLI models

Just like how the digital internet relies on the OSI (Open Systems Interconnection) model to organize and regulate data exchange, the Physical Internet (PI) adopts its own framework, the OLI (Open Logistics Interconnection) model. This model acts as a blueprint for managing the flow of goods, information, and financial transactions within the PI network. It sets out different layers of interaction and protocols, guiding how different parts of the system communicate and work together smoothly. Through this structure, the PI ecosystem can achieve seamless integration and collaboration among its nodes, carriers, and stakeholders. The model also proposes seven layers to offer a richer representation.[Montreuil et al., 2012]

- Physical Layer: The physical layer deals with moving and operating PI-containers using PI-movers. The physical layer ensures that the physical connections within the Physical Internet are standardized.
- Link layer: The link layer focuses on detecting and possibly correcting unexpected events that arise from operations at the physical layer. It does so by ensuring

consistency between physical operations and their digital counterparts.

- Network layer: The network layer is all about making sure that networks within the Physical Internet are connected smoothly, operate reliably, and can work together seamlessly.This layer also defines the composition and decomposition of π-containers, the assignment and control of flows of containers across π-networks.
- Routing layer: At this layer, π-routing protocols are established, implemented, and managed. It keeps track of the status, service capability, capacity, and performance of all π-means within each π-network.
- Shipping layer: The shipping layer establishes the functional and procedural methods necessary for an efficient shipping of sets of π-containers from shippers to final clients. It organizes, oversees, and finalizes the shipment process between the shipper and each client.
- Encapsulation layer: The encapsulation layer is responsible for providing the necessary procedures to efficiently package a user's products into uniquely identified π-containers before they enter the Physical Internet networks.
- Logistics Web layer: The Logistics Web layer acts as the intermediary between the Physical Internet and logistics service users, providing the necessary procedures for users to utilize the Physical Internet effectively. This layer facilitates dynamic decision-making regarding product supply, manufacturing, distribution, and mobility within a globally connected Logistics Web enabled by the Physical Internet.

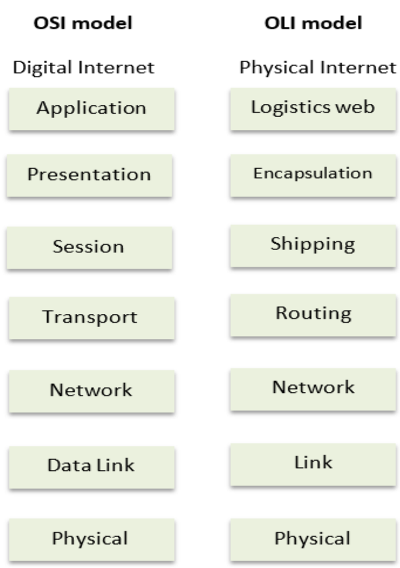

Figure 1.15: OSI and OLI models

Digital Internet and Physical Internet similarities

The main similarities between PI and DI can be summarized in five main points : users, unit of flow, routing of the flow, carrier of the flow and protocols.

- **Users**: Just as the digital internet serves as a platform for private and commercial users to exchange information and services, the Physical Internet allow private and commercial users to exchange physical goods. In both cases, users interact with the network to send or receive items.

- **Unit of Flow**: The digital internet operates by transmitting data packets, which are the fundamental units of information exchange. Similarly, the Physical Internet transmits standardized modular units which are the PI-containers, as the basic carriers of physical goods. These units ensure a seamless transfer between different nodes and modes of transportation within the PI network.

- **Routing of the Flow**: In the digital internet, data packets are routed through a network of interconnected nodes using the routers. Likewise, in the Physical Internet, PI-containers are routed through a network of interconnected PI-nodes.

- **Carrier of the Flow**: In the digital internet, data packets are carried across the network by various communication channels, including wired and wireless connections, fiber-optic cables... Similarly, in the Physical Internet, goods are transported between PI-nodes using PI-movers and by various modes of transportation.

- **Protocols**: Both the digital internet and the Physical Internet rely on standardized protocols to ensure compatibility, interoperability, and security within their respective networks. In the digital realm, protocols like TCP/IP.. Similarly, in the Physical Internet, protocols define how PI-containers are handled, transported, and exchanged between different nodes and carriers, ensuring seamless integration and operation within the PI network.

	Physical Internet	Digital Internet
User	Private and commercial shippers	Private and commercial users
Unit of flow	Modular and standardized PI-containers	Data packets
Routing of the flow	PI-nodes	Routers
Carrier of the flow	PI-movers with different transportation modes	Physical media (optical fiber...)
Protocols	Standardized sending/receiving processes	TCP/IP protocol

Table 1.1: DI and PI similarities

Differences between the DI and the PI

Same for differences between Physical and Digital Internet, the differences can be sorted into five major categories: cost, time, schedule, emissions and capacity.

- **Cost**:The cost of transmitting and processing data over the digital internet is generally much lower compared to the physical movement of goods and it depends only on the electricity consumption. But in the physical internet the transportation and handling of physical goods incur tangible costs, including transportation, holding, handling and fuel costs.

- **Time**: Data transmission over the digital internet is nearly instantaneously and negligible, with data packets traversing the network at the speed of light through fiber-optic cables or via wireless communication. In the other hand the transit times for physical goods within the PI network depends on various factors, like the distance, transportation mode and the congestion and it can take very long time.

- **Schedule**: Digital communications and transactions can occur asynchronously and instantaneously, allowing users to send and receive data at any time without strict adherence to predefined schedules. For the physical internet the scheduling of physical shipments within the PI network depends on numerous factors such as transportation capacity, route availability, demand fluctuations and logistical constraints. As a result, scheduling physical shipments often requires actually an advance planning.

- **Emissions**: Data transmission over the digital internet generally has a lower and negligible environmental footprint compared to physical transportation, as it consumes less energy and generates fewer emissions per unit of information exchanged. But the transportation of goods within the PI network can contribute to greenhouse gas emissions and environmental pollution which actually proportional to the goods delivery.

- **Capacity**: The digital internet has virtually unlimited capacity for transmitting and storing data, thanks to the infrastructure and to different technologies such as cloud computing and distributed networks. For the physical internet the capacity of the PI network to handle physical goods is constrained by infrastructure capacity, vehicle fleet availability, storage space, and handling capabilities at PI-nodes.

	Digital Internet	Physical Internet
Cost	Electricity consumption cost	transportation, loading an unloading cost
Time	negligible	Significant
Schedule	transmission almost instantaneous	dynamic process
Emissions	Fixed cost, negligible	proportional to the goods delivered
Capacity	flexible, more critical	Sophisticated capacity management

Table 1.2: DI and PI differences

1.2.3 Physical Internet road-map

ALICE : Alliance for logistics innovation through collaboration in Europe

The European technology platform ALICE is set-up to develop and implement a comprehensive industry lead strategy for research, innovation and market deployment in the field of logistics and supply chain management in Europe. It is currently researching and working about PI in collaboration with other companies in several fields for the deployment of this concept all over the world.

ALICE has worked on several projects, among these projects we find the SENSE in which a Physical Internet road-map was developed to explain the development of PI over the next years over five areas of research:

- Logistics nodes : The concept of the Physical Internet anticipates transforming Logistics Nodes into Physical Internet nodes, characterized by standardized operations and protocols, the utilization of a range of standard and interoperable modular load units, autonomous hubs and automated material handling.

- Logistics Networks : PI Networks are expected to develop door-to-door services that are seamless, flexible, and resilient. These services aim to consolidate and deconsolidate all shipments within a logistics network, ensuring that all capabilities and resources are seamlessly visible, accessible, and usable. It also consists on defining routing algorithms, rules and protocols.The ultimate goal is to maximize the efficient utilization of these resources within the network and a real time connectivity among the networks.

- System of Logistics Networks: The Logistics Networks System is the foundational framework of the Physical Internet, demanding secure, efficient, and extensible services to facilitate the seamless flow of goods, information, and finances across logistics networks. The objective is to share gains and to ensure a global interconnectivity.
- Access and Adoption : Definition of the main requirements to access the Physical Internet through a logistics network.
- Governance : Defined by stakeholders rules, sustainability and to build trust among users.

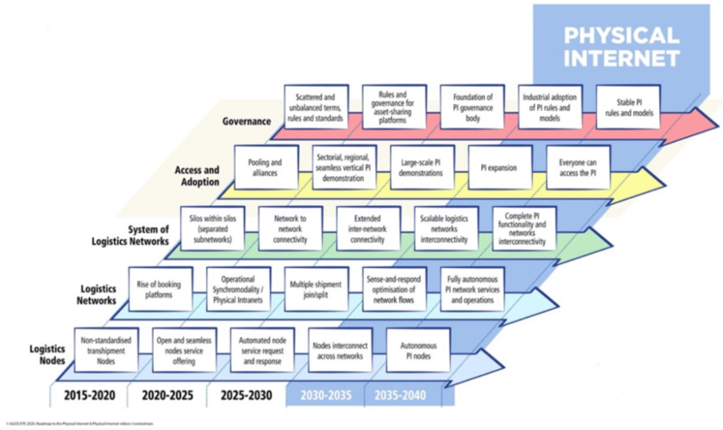

Figure 1.16: Physical Internet roadmap

A simulation experiment with Top retailers Carrefour and Casino in France and their 100 top suppliers was made to test the effectiveness of Physical Internet model. the results showed a potential for **32%** increase in profits, **60%** reduction of greenhouse gas emissions and **50%** of volume shifted from road to rail.

ALICE aims to make the Physical Internet a reality by 2030s with autonomous PI-nodes,stable PI-rules and models,interconnected nodes across the network where everyone can just access the PI.

1.3 Problems classification

Physical internet problems can be classified into two major groups [Chargui et al., 2022] :

- **Facility problems** where the problems related to the PI-Hubs design,scheduling, optimization and the internal routing are studied.
- **Network problems** where the problems related to the network design, the interconnectivity,the location of PI-Hubs and the routing in a Physical internet network are studied.

1.3.1 Facility problems

Rail-Road and Road-Rail PI hubs

Many works and papers studied this type of PI hubs. Starting with [Ballot et al., 2012] that developed a functional design of Rail-Road PI hubs, the purpose of a PI road-rail node is to enable the transfer of PI containers from their inbound to outbound destinations. The authors provide an explanation of how PI-containers, vehicles, and trains move within the PI-hub. They were interested on two sets of key performance indicators (KPIs), from the customer's and from the operator's Perspective.

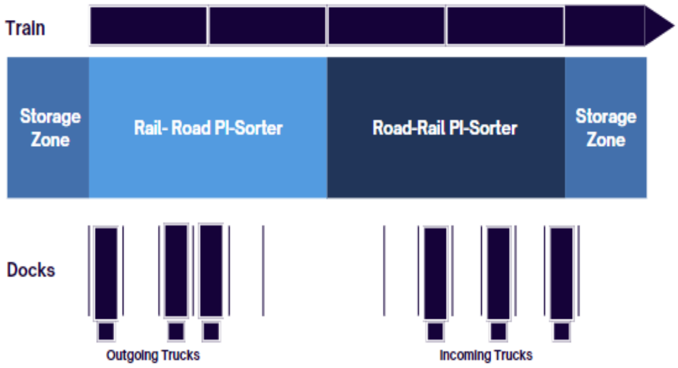

Figure 1.17: Rail- road and Road-Rail Pihub layout

Other works studied Rail-Road PI-hub optimization. Starting with this paper where [Walha et al., 2014] studied rail-road allocation and scheduling problem . This involves allocating each container to its truck and then assigning the docks to the correct destination. The -containers must be transferred from wagons to outgoing -trucks using the rail-road -sorters. The problem is identified as a special bin packing problem and the main performance objective is defined as the combination of two criteria to minimize :the number of used trucks and the distance covered by each container to reach the dock destination. Considering that the position of both containers and trucks affected to docks are changing over the time and that the containers are considered with same priority. This study proposed an heuristic based approach and a linear model and they are implemented in java and CPLEX respectively . In [Pach et al., 2014], a potential fields approach was developed to manage the unloading of a train, the routing of active -containers and the loading into trucks in rail-road PI hub context. The system was designed and simulated using Netlogo. This paper aims to examine the effectiveness and robustness of the routing mechanism considering many assumptions to make the system in critical conditions(considering a maximum number of -containers to manage and that the trucks are not properly aligned).The main performance indicator measured in the simulations is the evacuation time. It represents the time between the unloading of the first -container from the train and the loading of the last -container on its truck.The results indicated that the system bottleneck lies in the loading process, and the suggested approach demonstrated a decrease in both evacuation and loading times. [Walha et al., 2015]also identified the problem as a special bin packing problem with an objective is to minimize the distance covered by each container considering that the assignment of trucks to the docks must be done before the arrival of the train and the contents of wagons are known about 1 h before the arrival of the train. This study introduces a simulated annealing meta-heuristic which is then compared to the best Fit Grouping heuristic and they are both implemented in java. Various scenarios were tested to compare the effectiveness of all the methods. [Walha et al., 2016]worked about the same problem using the best Fit Grouping heuristic and simulated annealing meta-heuristic but also introducing a multi-agent based approach to generate reactive solutions and to deal with perturbations in a realistic context (considering the availability of the docks perturbation) and it was implemented in JADE.

[Chargui, 2020]integrated energy consumption into the objective function. Several multi-objective approaches were introduced aiming to ensure the sustainability by minimizing both the cost of vehicle use as well as the energy consumption of PI-conveyors. Starting with the multi-objective model (MO-MIP) that formulated the problematic aiming to find the grouping of PI-containers as well as the allocation and planning of vehicles on the docks. The model is always implemented on CPLEX. A construction heuristic H0 and two meta-heuristics were subsequently introduced to adress the problem (MO-VNSSA et MO-VNSTS). These methods were implemented on C++. [Essghaier et al., 2023]studied the problem of uncertain multi-objective truck scheduling in Rail -Road PI-hubs. The problem was formulated as a fuzzy multi-objective mixed integer program (FMO-MIP) model considering two criteria to minimize which are the delay of trucks and the traveled distance of containers considering an uncertain arrival time of trucks that was defined as triangular fuzzy number. The resolution approach combines PI-constraint method for the minimization of the objective function and chance-constrained programming for uncertainty handling. The results of this work demonstrated that considering uncertainty during optimization process leads to an improvement in the quality of results and to obtain more robust solutions for case study.

[Chargui et al., 2018a]considered a Road-Rail Pi-hub assignment problem where the PI-containers are unloaded from the trucks and transferred through the PI-Sorter and then loaded into the wagons. A mixed integer linear programming MILP model was developed with the main objective to minimize the number of used wagons and the total internal traveled distance of PI-containers considering that the inbound trucks can unload containers with different lengths, and each one of those containers has a specific destination, PI-containers with the same destination must be loaded in consecutive wagons, each one of the train's wagons must load only PI-containers that have the same destination and finally for simplification, one block of 5 wagons is considered for loading the PI-containers. A tabu search meta-heuristic was proposed to solve this model, starting by the assignment of the containers to the wagons where the first fit bin packing algorithm of Johnson was used to generate the first solution that was improved by Tabu search meta-heuristic to find all the possible combinations and they were both implemented in C++. [Chargui, 2020]also studied this problem. At first a MILP was proposed with the objective of minimizing the number of wagons used, the distance traveled by the PI-containers from the vehicles to the train wagons as well as the delay of the vehicles on the platforms considering wagon's capacity and PI container's destinations constraints and the model was implemented on CPLEX. Then a multi agent system combined with 3 hybrid meta-heuristics (VNS-SA, GRASP-SA et TS-SA) was proposed ,based on the same objective and constraints. The three hybrid meta-heuristics are developed in Java and the agents are created and implemented in the JADE platform (Java Agent Development framework).

[Chargui et al., 2019]developed a simulation-optimization approach to optimize Rail-Road and Road-Rail PI hub. This work aims to develop a robust solution that can handle unexpected perturbations(PI-conveyors failure). They suggested a mixed integer linear programming model with an objective to minimize the number of used wagons and outbound trucks, the distance traveled by PI-containers form inbound trucks to the wagons and from the wagons to the outgoing trucks and finally the tardiness of inbound trucks and the end time of processing outbound trucks. for the resolution approach they combined the Modified Threshold Accepting meta-heuristic and a perturbation simulator which generates perturbations at each local iteration of the MTA meta-heuristic to ensure that each new generated solution S is robust before considering it as the current best robust solution.

	Meta-heuristics	heuristics	Simulation
[Walha et al., 2014]		x	
[Pach et al., 2014]			x
[Walha et al., 2015]	x	x	
[Walha et al., 2016]	x	x	x
[Chargui, 2020]	x	x	x
[Chargui et al., 2018a]	x	x	
[Chargui, 2020]	x		x
[Chargui et al., 2019]	x		x

Table 1.3: Resolution approaches

1.3.2 Network problems

Starting with [Montreuil et al., 2013], they studied the interconnectivity in the context of Physical Internet similarly to the case of Digital Internet. From a logistic perspective, the interconnectivity refers to making the transportation and transfer of physical goods smoother and easier, to handle their storage and treatment efficiently and finally to share the responsibilities between the different actors and stakeholders within the logistics chain. Universal interconnectivity is the key to make Physical Internet an open, global, efficient and sustainable system.

They supposed that universal interconnectivity could be attend through physical, digital and operational interconnectivity :

- **physical interconnectivity:** The idea is to guarantee a seamless movement of Physical objects within the Physical Internet network by encapsulating the goods in standardized and modular containers.
- **Digital interconnectivity:** It is about ensuring a meaningful information exchange between the different nodes and actors of our PI network. This includes the tracking of objects using the Internet Of Things.
- **Operational interconnectivity:** It consists on using business constraints and respecting operational protocols to make the exploitation of Physical Internet easier.

[Sarraj, 2013]proposed in his work the main concepts,protocols and the operating principles for the routing of PI-containers in the physical internet network. He supposed that the Physical Internet would have a hierarchical architecture in the form of several autonomous systems(AS) where a node will no longer have knowledge of the complete state of the network but only that of the SA to which it belongs. A routing algorithm based on the juxtaposition of arcs was introduced for the routing in PI supply chain network. His studies were based on a real supply chain network in France 1.4 and he considered three databases: real flows of mass retail products: liquids, groceries and DPH (Drugstore, Perfumery and Hygiene)like mention in **??**.Infrastructure (roads, rails) from original IGN© and finally a PI network, this database was the subject of research work carried out by EPFL-Lausanne in Switzerland during the research project carried out with PREDIT. A multi-agent model based on the discrete event approach, implemented in XJ's AnyLogic simulation software was introduced as a resolution approach. Various scenarios are tested to evaluate the performance of the network considering many key performance indicators (KPI): Economic, Environmental and societal KPIs. The results of this simulation demonstrated that PI gives very encouraging results. The load is increased by almost 20percent the use of rail transport leads to a 60percent reduction in CO_2 emissions in France, this also includes a reduction on delivery times. Finally, all the scenarios showed a reduction in transport costs comparing to the classical SC (between 4percent and 33percent depending on the scenarios).

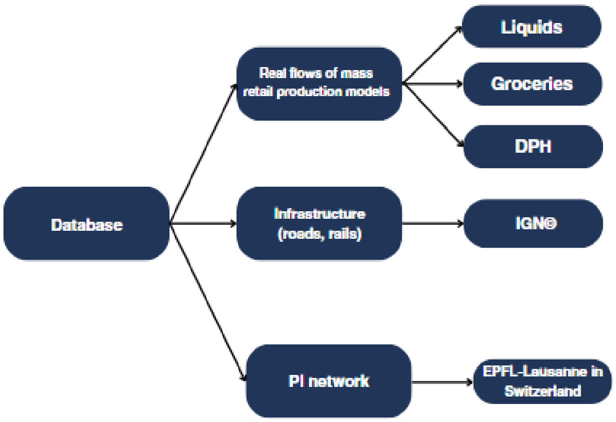

Figure 1.18: Database

Nodes	Facilities	Warehouses	Distribution centers	Total
Number	303	57	58	418

Table 1.4: Network nodes.

The work of [Fazili et al., 2017] is based on [Sarraj, 2013] paper. In order to understand the Physical Internet (PI), the conventional (CO), and the hybrid (HY) logistics systems, a simplified road network in Eastern Canada was considered. Eleven cities in eastern Canada are the nodes in the network (The network has a tree structure) and only five of this nodes are PI transits (using maps.Google.com). VRP-like routing and BPP (Bin packing problem)techniques are used in this paper .A three-phased optimization framework was proposed to compare the performance of logistic systems based on Monte-Carlo simulation: Container packing optimisation,Truck routing optimisation and Truck scheduling optimisation. Physical internet demonstrated superior performance from an environmental point of view and it benefits from lower total driving time and social costs associated with truck driving. Finally, the results showed that the efficiency of PI depends on the efficiency of its transit centers.

[Yang et al., 2017] were interested in a single-product inventory problem with network supply disruptions with uncertain demands and stochastic supply disruptions. The main objective of this work was to minimize the total annual logistics costs and to determine suitable inventory control decisions. A simulation- optimization approach with heuristic based on a dynamic source selection strategy named Minimum Distance strategy from [Pan et al., 2015] and Pan et al. (2015) works was proposed. Many scenarios were tested to evaluate the performance of the physical internet supply chain network. The results of their experiments indicate the superiority in terms of resilience of the Physical Internet inventory model against classic inventory models. His studied were also based on a real network in France 1.19

[Kantasa-Ard et al., 2021b] worked about demand forecasting in the context of Physical Internet. This studies were based on a real network in the lower northern region of Thailand, this network is composed of one production lines, three hubs and two retailers. The experimental data were obtained from the Thai Office of Agriculture of the consumption of Corn, Pineapple and Lassava for the period from January 2010 to December 2017. As a resolution approach they proposed a machine learning resolution

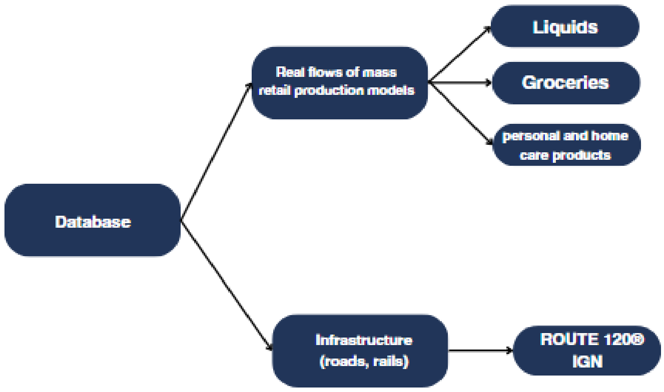

Figure 1.19: Network database

approach to improve the predictions because classical methods have many limitations. At first, they proposed a forecasting model based on LSTM(Long short term memory) recurrent neural network, then they tuned the hyper-parameters of the model using a hybrid meta-heuristic combining Genetic algorithm and Scatter Search to improve the predictions.Finally, they simulated the Physical Internet network using forecasting data to evaluate its performance on reducing holding and transportation cost.The model was then introduced in NetLogo multi-agent plateform. The results showed a variation of around 0.09–1% in holding costs when comparing forecast and real demand, and a range of 0.3–1.07% in transportation costs.

In [Kantasa-Ard et al., 2021a], a multi depot vehicule routing problem (MDVRP) was studied and compared between classical supply chain and Physical internet. The problem of routing was formulated with a Mixed Integer Linear Programming (MILP) model and this research focuses only on the delivery part from PI-hubs to retailers. Two main assumptions were considered: first the truck can return to the closet hub and it is not forced to return to the starting hub, and secondly inventory level at each hub were considered and not only trucks capacity. The experiment was based on real data of the daily forecasting demand of a commodity crop in the Thailand's northern region from [Kantasa-Ard et al., 2021b]. For the problem resolution, a random iterated heuristic was proposed to generate the first solution that was improved using Nearest Neighbor Search (NNS). The results of the two solutions (MILP and IRH) were performed by comparing the transportation cost and computational time. The results showed that IRH-NNS demonstrated better performance for a large number of PI-hubs and retailers and it takes less computational time than the MILP method. For a realistic context, a vehicle routing problem with simultaneous pickup and delivery problem VRPSPD [Kantasa-ard et al., 2023] was after that proposed to solve routing problems always in the context of Physical Internet. As a resolution approach a MILP, Itarated random heuristic and two meta-heuristics (Simulated annealing and random local search) were introduced always comparing transportation and holding costs.

[Nouiri et al., 2021] proposed a multi-agent model to compare the performance of a Physical internet network with the one of a classic supply chain based on transportation and holding costs as main performance indicators to measure and compare the resilience of the network. The model was proposed to generate reactive solutions and to deal with external perturbations in a realistic context. Each agent in the model represents a node in the Physical Internet (hub, plant, and retailer) or a transportation link (truck) between nodes. External perturbations were simulated as periods of unavailability at a random hub or distribution center, based on three levels of unavailability: low (node unavailable 1 day), medium (unavailable between 3-5 days) and high (5-8 days of unavailability). In the case of PISCN three replenishment policies were defined: Random, closet and hybrid method. The model was tested on a real network composed of one plant, three hubs and two retailers based on real data of monthly white sugar consumption rate from January 2015 to September 2019 in Thailand. The results of the simulation demonstrated the efficiency of PISCN compared to the classical SCN especially for the transportation cost. The simulation results also showed the importance of the replenishment policy on transportation and holding costs.

[Peng et al., 2021] studied a many to many network structure (many plants supply many retailers). In this paper the physical internet key components were captured, Physical Internet resilience was studied and pre-event(additional production, storage, and handling capacities,) and post-event (Reconfiguration of flows and the recovery from any production, storage, and handling capacities) mitigation strategies were considered. A two-level heuristic algorithm was proposed for the problem resolution. The results of this work showed that using the interconnectivity between the PI-nodes will increase the flexibility achieved by our Physical Internet system.

[Cassan et al., 2023]proposed a new capabilities-based theory for routing and data sharing in the PI network. PI capabilities refer to the specific services or functionalities offered at PI nodes.They supposed that the network is created by combining the PI-nodes with their PI-capabilities with a set of PI-transporters and they proposed that the network is decentral .A shortest-path algorithm was then build to find routes for containers depending on their performance. The performance is represented by an objective function that aims to minimize distance, monetary cost, duration and greenhouse gas (GHG) emissions. The algorithm was then validated using an Agent-Based Model (ABM). The results showed that this approach is feasible and can be applied in a decentralized system.

[Luo et al., 2021]A Physical Internet-enabled customized furniture delivery system(PI-CFDS) was introduced in this article. At the beginning they considered a PI-enabled smart logistics facility where they focused on PI-containers and material handling processes and their effects on transportation time, costs and profits. On second place, they introduced a mathematic modelization of a VRPSPD with profits maximization and a Genitic algorithm meta-heuristic for problem resolution. Finally they based this research on a real-life data of a leading customised furniture service in China. The results showed that Physical Internet demonstrated superior performance than the traditional solution in most of cases.

In [Peng et al., 2020] work, an integrated production inventory-distribution system was addressed always to study the sustainability of the Physical internet network. The problem was represented as a a multi-objective mixed integer linear programming model (MOMILP) with three different objective functions, each one represents and aspect out of the three aspects of sustainability. The economic aspect is represented by the total cost that combines production, loading and unloading, inventory and transportation cost. The environmental objective is measured by the overall green house gas emissions of all the network using a fuel conversion factor to assess GHG emissions based on fuel consumption. Finally the social aspect is calculated based on the social impacts of accident risks in all periods. The model was solved using using the augmented ϵ–constraint method, than the sustainability performance of the PI-enabled model was compared with that of models enabled by the traditional (TR) and horizontal collaboration (HC) networks. The results show that the PI actually showed better performances in term of different objectives and it guarantee significant sustainability performance advantages.

Conclusion

In summary, this chapter addresses the need for innovative solutions in global logistics to address economic, environmental, and societal challenges. Traditional supply chains are insufficient, and the Physical Internet offers a transformative approach. By using standardized containers and dynamic routing, it aims to improve efficiency, reduce costs, and lower environmental impact. We also highlighted ALICE's role in promoting logistics innovation. Embracing the Physical Internet's principles will help create more resilient, efficient, and sustainable supply chains for the future.

After classifying different articles about the physical internet, We have chosen to focus on addressing the vehicle routing problem, recognizing its significance in optimizing logistics operations while introducing an innovative concept of physical internet which is the PI-containers. In the next chapter, we will discuss the PI-containers in detail.

Chapter 2

PI-containers

Introduction

The Physical Internet (PI) proposes a new way of handling logistics and transportation, similar to how the internet changed communication. At the heart of this idea are PI-containers—standardized, modular, and smart units that make it easier to move goods all over the world.

PI-containers need to meet specific physical and informational standards. Physically, they are designed to be compatible and durable, making them easy to handle and secure during transport. Informationally, they have advanced tracking and communication technologies that provide real-time updates on their status and location.

In this chapter, we will delve into the different types of PI-containers, their design considerations, and their role in shaping the future of logistics. We will explore how these containers relate to each other and how they differ from traditional methods of packaging goods. Additionally, we will discuss the importance of efficient routing in optimizing delivery times and reducing costs, including the role of protocols like Border Gateway Protocol in the PI routing process.

2.1 Requirements for the PI-containers design

The main principle of the PI concept revolves around using standardized containers as the primary unit loads. Instead of directly handling physical goods, the PI system encapsulates them within these standardized containers. These containers are then transported, managed, and stored throughout the PI network.

2.1.1 Physical requirements

According to [Sallez et al., 2015] PI-Containers encompass different requirements and functional specifications:

- Available in different modular sizes from large cargo containers to smaller dimensions.
- Designed to be effortless and easy to handle, store, transport interlock, load, unload, construct compose, decompose and transport.

- Constructed using eco-friendly materials with minimal environmental impact. They have to be also efficiently reusable and recyclable and to have minimal offservice footprint.

- Reduce the need for additional packaging materials like pallets, boxes, cases...

- Equipped with conditioning features such as temperature and humidity control when needed. For example while transporting perishable products.

- They are sealable to ensure the security of the goods contained in the containers during transportation, storage, or handling.

PI-containers can be classified into three main categories based on their Physical design requirements: transport, handling and packaging containers.

- **Transport containers or T-containers** :They are large entities transported by the different types of vehicles (trucks, trains, ships. . .) on the PI networks. They're made to be easy to carry, tough enough for harsh conditions, and stackable like regular shipping containers used in maritime transport. They can contain directly physical objects or containers of smaller size. They have all the same width and high (2.4m*2.4m) but with different lenghts(1.2, 2.4, 3.6, 4.8, 6 or 12 m).

- **Handling containers or H-containers** :They are designed to be handled by PI-handlers (conveying systems, lifts. . .) and to resist handling conditions in the PI-nodes.They can also contain physical objects or containers of smaller size.The standard maximum external size of an H-container enables it to fit inside a T-container with external sides measuring 1.2 meters. Smaller modular dimensions along the X, Y, and Z axes range from approximately 50%, 40%, 30%, 20%, down to 10% of this maximum size.

- **Packaging containers or P-containers** :They are the smallest type of PI-containers and they are used to contain directly the physical goods. They're made to easily fit inside H-containers, being thin and lightweight for effortless handling. They protect the product and can be stacked when required.Essentially they are designed to replace custom packaging.

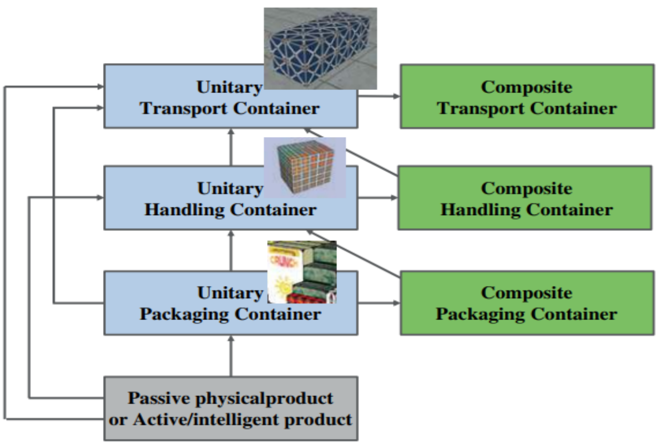

Figure 2.1: PI-containers [Sallez et al., 2015]

Relationship between PI-containers categories

There is two existing types of relationships between the PI-containers:

Encapsulation

To better understand the concept of encapsulation in the Physical Internet, I will introduce at first the current state of goods encapsulation and then compare it with the case of Physical Internet. This is proposed by [Montreuil et al., 2015]

- **Current state of goods encapsulation**
  In the current state of encapsulation, we have five main tiers based on the type of the used packaging: goods packaging, basic handling unit loads, palletizing, Shipping containers and Transportation carriers.

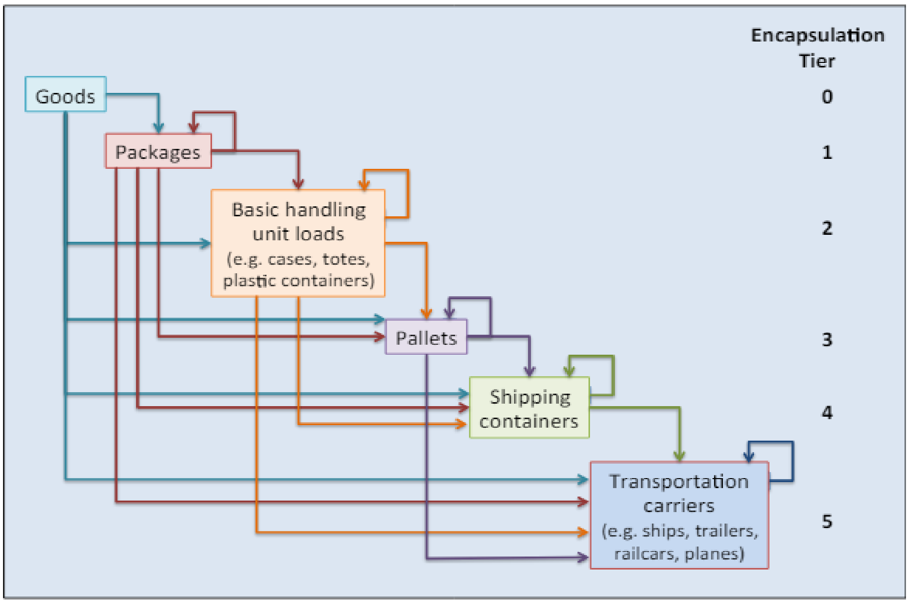

Figure 2.2: Current state of goods encapsulation [Montreuil et al., 2015]

In the first tier of encapsulation: **goods packaging**, physical products are packaged in boxes, plastic or glass bottles and plastic bags, this package is usually the final form of packaging and the basic selling unit of goods to retailers, businesses and consumers 2.3.

Figure 2.3: Goods packaging

The second tier: **basic handling unit loads** where products are grouped into basic handling units such as cases, totes and containers. Cases are most of the time designed to be used only once, but totes and plastic containers are reusable. The cubic form of cardboard cases makes them easier to handle and transport and their low price often leads users to use them once and adopt a throw-after-usage instead of passing by reverse logistics 2.4.

Figure 2.4: Basic handling unit loads

The third tier : **palletizing** where Unit loads like cases and reusable plastic containers are assembled and packed onto pallets for efficient handling. They are tightly secured with shrink wrap to maintain stability during transportation and minimize the risk of damage. Pallets are available in different dimensions and sizes. There are some standardized pallets such as the Euro-Pallet in Europe.

Figure 2.5: Palletizing

The fourth tier : **Shipping containers** : that contains either combination of products themselves in their unitary packaging or in a basic handling unit loads such as cases. This cases are either stacked directly on its floor or loaded on pallets. Shipping containers are tough and built to handle harsh environmental conditions like rain, snowstorms, sandstorms and seas.

Finally in the last tier : **Transportation carriers** where goods are loaded into carriers like trucks, wagons and airplanes so as to be transported from their source to their destination and final clients. Each mode of transportation offers its own set of advantages and it is chosen based on different key factors like distance, urgency, cost, delays and nature of the goods being transported.

- **Physical internet and goods encapsulation**

Figure 2.6: Shipping containers

Figure 2.7: Transportation carries

The Physical Internet concept suggests replacing the different types of packages, cases, totes, and pallets used in encapsulation tiers in the classical supply chain with standardized and modular PI-containers. However, these containers need to be available in different structural sizes to effectively respect and satisfy the wide range of intended uses.
For this, three different types of PI-containers with different sizes were proposed and designed : transport containers(T-containers), handling containers(H-containers) and packaging containers (P-containers).
The concept of encapsulation in the Physical internet consists on encapsulating goods in P-container, then the P-container are encapsulated in H-containers and finally H-containers are encapsulated in T-containers. But at the same time, goods can be directly be encapsulated in H-containers or T-containers and H-containers directly in T-containers without needing and using the P-containers. (2.9) demonstrate the case of encapsulation of H-containers in T-containers proposed by [Montreuil et al., 2015]

The difference between both encapsulation concepts in the current state and in the Physical internet are resumed in the table below. In the current state of encapsulation we have 5 different tiers of packaging but in the Physical Internet only four tiers are proposed.

Current state	**Physical Internet**
Packages	Transport containers
Basic handling units loads and pallets	Handling containers
Shipping containers	Transport containers
Transportation carriers	PI-movers

Table 2.1: Comparison between encapsulation in the current state and in the Physical Internet

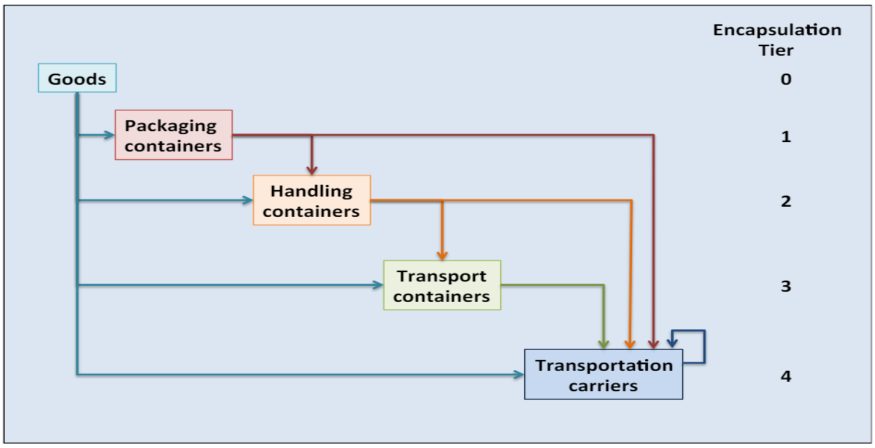

Figure 2.8: Goods encapsulation in the Physical Internet [Montreuil et al., 2015]

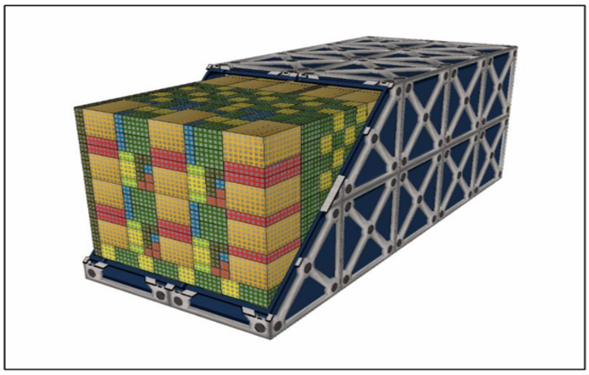

Figure 2.9: Encapsulation in the Physical internet [Montreuil et al., 2015]

Composition

The PI-Containers are modular and can be composed together and decomposed also. Composite PI-containers allows easier handling and transport.

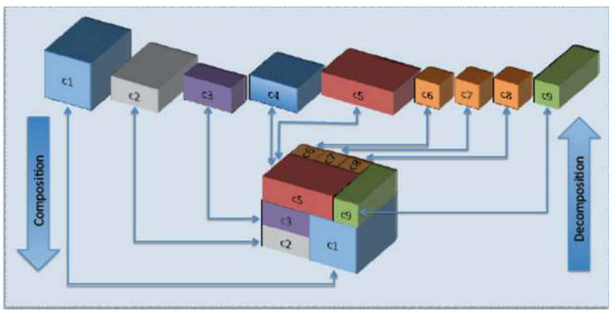

Figure 2.10: Composing and decomposing PI-containers [Sallez et al., 2016]

2.1.2 Informational Requirements

To provide information effectively about the containers, specific informational requirements need to be met. Today, various technologies such as GPS, the Internet of Things (IoT), and digital twins can greatly help in achieving this goal [Sallez et al., 2015] [Sallez et al., 2016]:

- **Identification:** Similar to MAC addresses on the Digital Internet,Every PI-container needs a distinct global identifier which is already specified by the EPCglobal standard: The GRAI code for Global Returnable Asset Identification. The GRAI can be encoded in a bar-code or EPC/RFID tag that can be scanned to automatically register the returnable asset's movements. [GS1 Algeria, 2024]

Figure 2.11: Structure of a GRAI code

- **Traceability and tracking:** The PI-management systems should be able to find and track each PI-container and provide detailed traceability information. This includes the container's status, location, as well as its arrival and departure dates at PI facilities. Additionally, these systems need to record environmental conditions when required, like temperature and humidity levels, to maintain the quality of the contents.
  The Electronic Product Code (EPC) is syntax for unique identifiers can be used and assigned to PI-containers to ensure their tracking. EPC have different representations including binary forms used on Radio Frequency Identification (RFID) tags which can be tailored to suit our specific needs and application

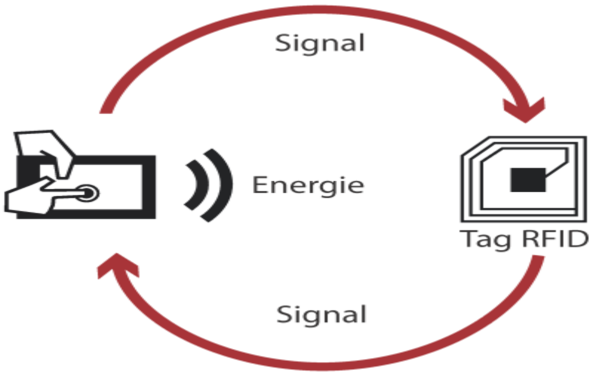

Figure 2.12: RFID Technology

- **Integrity:** The PI-management systems play a crucial role in ensuring the integrity of the cargo in the PI-containers. This involve monitoring compliance with the cold chain requirements for perishable goods and detecting any deviations that could compromise product quality. Additionally, these systems are responsible for tracking and preventing incidents such as unauthorized container openings, which helps prevent theft and ensures the security of the cargo throughout its journey.

- **Confidentiality:** Only authorized parties and stakeholder should have access to the contents of our PI-container in PI-network based on their permissions. These containers should act as "black boxes" to all other participants in the PI-network. Achieving this involves encrypting data and implementing strict access control measures.

- **Communication capabilities**: PI-containers must be intelligent and have the ability to communicate between each other to facilitate compatibility checks during transportation and storage. In Modulushca project, it was proposed equip H-containers with both long and short-range communication technologies, such as Zigbee, EnOcean, and LoRaWAN, for tracking and localization.

- **Decision capabilities**: PI-containers should have the ability to autonomously make decisions. For instance, they could determine the most efficient transport route from the origin to the destination at the physical internet network level. Similarly, at the PI-hub level, they could optimize handling and sorting movements.

2.2 Routing of the PI-containers

In the realm of PI-container routing, many algorithms have been proposed in literature, with many relying heavily on the Dijkstra algorithm to determine the shortest path between nodes. However, in my current work, I intend to explore and mention the algorithm developed by which leverages the Border Gateway Protocol (BGP). This algorithm combines BGP's strengths with the needs of PI-container routing, promising better performance for these networks. By merging BGP's routing decisions with container-specific needs, it opens up an effective way to enhance PI-container network efficiency.

I'll start by explaining how the BGP algorithm works in digital internet, highlighting its features. Then, I'll move on to discussing BGP in the context of physical internet.

2.2.1 Border Gateway protocol in the digital internet

Definitions

Border Gateway Protocol (BGP) refers to a gateway protocol that enables the internet to exchange routing information between autonomous systems (AS). As networks interact with each other, they need a way to communicate. This is accomplished through peering. BGP serves as the mechanism enabling this communication and it makes peering possible. . In the absence of BGP, networks would be unable to effectively transmit and receive data with one another[Fortine,].

[Burke, 2023] Each router has and manage a routing table that guides packet routing. The BGP process on the router generates routing table data based on the following factors:

- Incoming information from other routers.
- Information in the BGP routing information base (RIB), which is a data table stored on a server on the BGP router.

The RIB includes data from both directly connected external and internal peers. It includes policies for route preferences and information sharing, updating the routing table as changes occur.

Characterizes of BGP protocol

- **Facilitates Inter-Autonomous System Communication**:
  BGP enables communication between two autonomous systems, fostering information sharing that would otherwise not be possible.

- **Next-Hop Paradigm Support**:
  BGP adheres to the next-hop paradigm, ensuring packets are directed to the most optimal router for faster network performance without requiring explicit configuration.

- **Coordination Among Multiple BGP Speakers**:
  BGP efficiently coordinates among multiple BGP speakers within an autonomous system, assessing various options to determine the best path for data transmission.

- **Path Information:**
  BGP advertisements include path information, detailing the next destination and reachable destinations, aiding in route selection.

- **Policy Support:**
  Administrators can implement policies within the BGP system, such as route prioritization between internal and external routes.

- **Transmission over TCP:**
  BGP operates over Transmission Control Protocol (TCP), ensuring compatibility with internet communication standards, including SSL, VPNs, and TLS.

- **Bandwidth Conservation:**
  BGP supports bandwidth conservation, optimizing network transmissions to maximize efficiency.

- **Support for CIDR**:
  BGP seamlessly integrates with Classless Inter-Domain Routing (CIDR), allowing for efficient allocation and management of IP addresses.

- **Security Integration**:
  While BGP lacks inherent security features, it supports existing security tools and protocols, enabling administrators to secure networks while utilizing BGP for routing.

The BGP Best Path Selection Algorithm

As provided by Cisco [Cisco, 2023], the algorithm can be summarized in the following steps:

- Prefer the path with the highest WEIGHT .

- Prefer the path with the highest LOCAL-PREF.

- Prefer the path that was locally originated via a network or aggregate BGP subcommand or through redistribution from an IGP .

- Prefer the path with the shortest AS-PATH : An AS-SET counts as 1, no matter how many ASs are in the set.

- Prefer the path with the lowest origin type.

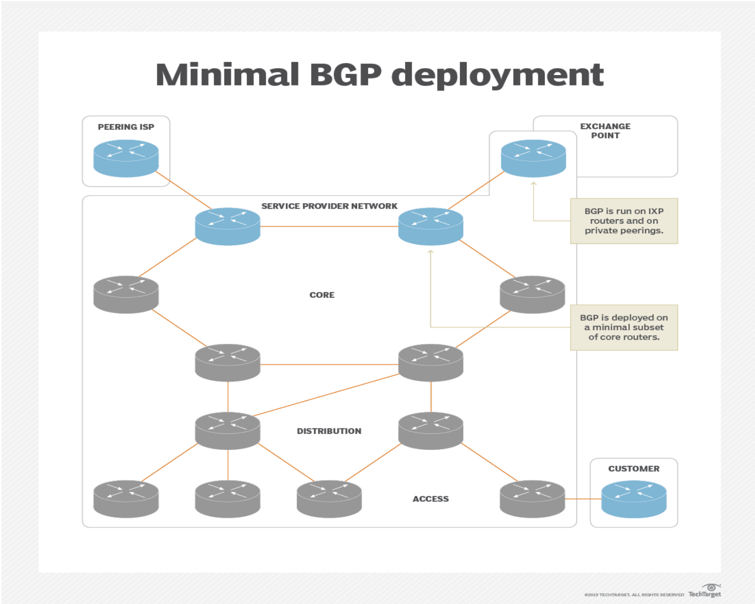

Figure 2.13: Border Gateway protocol

- Prefer the path with the lowest multi-exit discriminator (MED).
- Prefer eBGP over iBGP paths.
- Prefer the path with the lowest IGP metric to the BGP next hop.
- Determine if multiple paths require installation in the routing table for BGP Multi-path.
- When both paths are external, prefer the path that was received first (the oldest one).
- Prefer the route that comes from the BGP router with the lowest router ID.
- If the originator or router ID is the same for multiple paths, prefer the path with the minimum cluster list length.
- Prefer the path that comes from the lowest neighbor address.

2.2.2 Border Gateway protocol in the Physical internet

Standards are important for the Physical Internet (PI) and its routing algorithm (PI-BGP). They ensure smooth and easy operations by considering factors like stop frequency at PI-Hubs, transportation time, waiting periods, and costs. All the informations that i will mention in this part are developed by [Gontara et al., 2018]

Standards

- **Standards for Compatibility**:
  Standards are crucial for ensuring operational compatibility and coordination in logistics. However, adopting standards can sometimes lead to a trade-off between adaptation and adaptability. Previous standards must be considered to maintain continuity between traditional logistics and the Physical Internet.

- **Consensus in Routing**:
  The PI-BGP routing algorithm aims to find a balance and a trade-off between the number of stops at PI-Hubs, transportation time, wait times, and costs between two different nodes. PI-Hubs, serving as nodes in the Physical Internet, can belong to the same PI-AS (Physical Internet Autonomous System) or different ones. This routing process resembles the BGP-4 protocol used in the digital internet.

- **Key Considerations for Standards in PI-BGP**:
  All PI-AS should adopt standardized sizes for PI-Containers to facilitate smooth transitions between different modes of transportation and PI-AS using PI-movers between different PI-nodes. The design of such containers is based on different physical requirements and informational requirements that I have already mention.

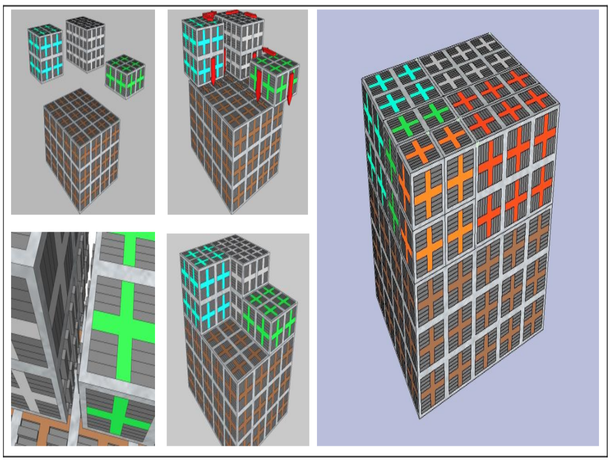

Figure 2.14: Modular design of PI-containers

Transitioning from traditional cross docks to PI-Hubs can improve efficiency by reducing delays. PI-Hubs enable faster unloading, sorting, and loading of PI-Containers compared to cross docks, resulting in significant time and resource savings. For the inter-transportation of PI-containers, PI-conveyors are generally used ensuring swift and seamless transitions between various transportation modes inside the PI-Hubs.

And finally the communication between neighboring PI-BGP nodes should be frequent and include updates on PI-Container characteristics, availability, costs, time estimates, and conditions of different roads and PI-Hubs. This communication ensures efficient routing decisions within the Physical Internet network.

Best practices:

The best practices for Logistic Service Providers (LSPs) participating in the Physical Internet (PI) are an outsourced companies that provides supply chain management services such as transportation, warehousing or distribution services. This

- **Fixed Schedule and Routes**:
  LSPs involved in the PI should establish fixed schedules for their transportation services and negotiate fixed routes. This ensures predictability and reliability in the movement of goods within the PI network.

- **Detailed Communication**:
  There should be thorough communication regarding the nature of PI-Containers

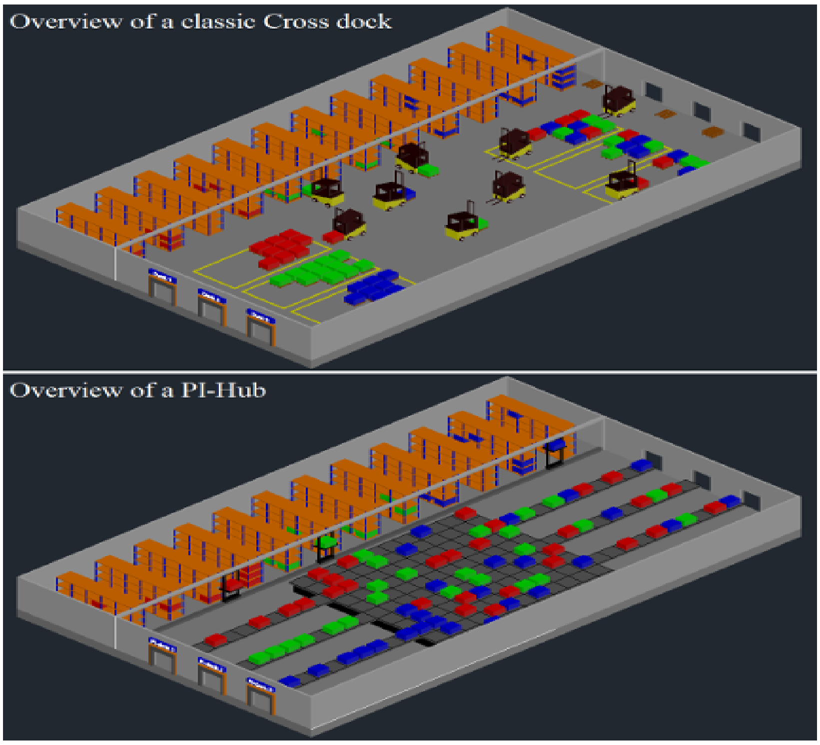

Figure 2.15: From classical to PI-cross docks [Chargui et al., 2018b]

and their specific requirements. This communication facilitates better coordination and collaboration between LSPs, enabling them to designate appropriate PI-BGP neighbors for efficient routing.

- **Recommendations for LSPs**:
These best practices serve as recommendations for LSPs operating within the PI framework. However, the actual implementation of these practices is subject to negotiation and agreement between the involved parties.

2.2.3 Selection of LSPs

The selection of Logistic Service Providers (LSPs) is a crucial aspect of building the Physical Internet (PI) infrastructure.

- **Outsourcing Logistics Operations:**
Companies often outsource their logistics operations to third-party providers known as logistics service providers (LSPs). These LSPs offer a range of logistics services to their clients.

- **Flexibility in Outsourcing:**
Clients have the flexibility to outsource either a portion or all of their logistics services to one or more LSPs, depending on their specific needs and requirements.

- **Formation of the Physical Internet:**
The Physical Internet is envisioned as a network of interconnected LSPs collaborating with each other, similar to Autonomous Systems in the Digital Internet. Therefore, LSPs participating in the Physical Internet are referred to as PI-AS (Physical Internet Autonomous Systems).

- **Choosing Suitable LSPs:**
  Selecting the most suitable LSPs to be part of the Physical Internet involves applying standards and best practices outlined previously. An Analytical Network Process (ANP) can be employed for this purpose. ANP allows for the evaluation of LSPs based on their adherence to standards and compatibility with the PI framework. This enables the identification of LSPs that are already using or willing to adopt standards aligned with the approach of the Physical Internet.

Conclusion

PI-containers are key to making the Physical Internet a reality, offering a practical solution to modern logistics challenges. With their standardized design and advanced technology, they streamline the movement of goods, making transportation more efficient and transparent.

As we implement the principles of the Physical Internet, PI-containers will play a central role in shaping a more connected and sustainable supply chain. By embracing innovation and collaboration, we can harness the full potential of PI-containers to revolutionize global logistics.

Chapter 3

A vehicle routing problem in a Physical Internet context

Introduction

In the context of the Physical Internet (PI), the vehicle routing problem (VRP) emerges as a critical challenge with substantial implications for logistics efficiency and sustainability. This chapter delves into the VRP within a PI framework, where the goal is to develop models that optimize vehicle routes for the delivery of goods using standardized, modular PI-containers. By addressing both single-period and multi-period scenarios, the chapter aims to present comprehensive methodologies to minimize transportation costs and improve the utilization of PI-containers.

The proposed models incorporate PI principles such as dynamic routing and modularity, highlighting their potential to enhance operational efficiency and reduce the environmental footprint of logistics activities. Through detailed problem descriptions, mathematical formulations, and application results, this chapter seeks to demonstrate the transformative impact of the Physical Internet on vehicle routing and logistics optimization.

3.1 Single-period model

3.1.1 Problem description

In the proposed model, we are working on a vehicle routing problem in a physical internet context. This problem involves operational routing of vehicles to efficiently meet the demands of our retailers expressed in term of PI-boxes while trying to minimize the free space inside the PI-containers.
The idea of PI-boxes that represents another aspect of PI principles was inspired from [Fazili et al., 2017] where they have introduced a multi-phase model. They have considered that demands are expressed in terms of PI-boxes with different sizes(fractional volumes) that will be transported using a set of PI-containers with a maximum capacity(fractional volume).
The main objective is to minimize at the same time the transportation costs and the empty space inside the PI-containers. The proposed model presents also the number of utilized PI-containers and their filling rates as decision variables to compare how the system will reacts under different cases.

Given a set of potential Hubs H where:{ h = 1, . . . , H } that are located to serve a set of retailers R: { i = 1, . . . , R } with different demands expressed in terms of PI-boxes P: { p = 1, . . . , P } using a set of PI-containers C: { c = 1, . . . , C }

3.1.2 Assumptions

The proposed model addresses the vehicle routing problem within the physical internet framework. Before we dive into our model, it's important to mention the assumptions guiding our approach:

- Demands are expressed in term of PI-box, that will be transported in PI-containers.
- PI-containers and PI-boxes have fractional volumes based on [Fazili et al., 2017] works. PI-containers have the same fractional size of 2, and four different fractional sizes for the PI-boxes of {0.25, 0.5, 0.75, 1}.
- There is a penalty cost associated with the remaining free space in the PI-containers.
- A retailer's demand can be satisfied using different PI-containers. Each retailer can be visited different times in a route.
- Hubs have an inventory level that must be respected.
- Hubs can share their different resources: trucks and drivers.
- The starting and ending hubs of a truck can be the same or different. The truck returns to the closet hub in the route.

3.1.3 Problem formulation

Notations:

$\mathbf{H}$	: Set of PI-Hubs
$\mathbf{I}$	: Set of retailers
$\mathbf{C}$	: Set of PI-containers
$\mathbf{P}$	: Set of PI-boxes
$\mathbf{D}_{hi}$	: Distance matrix between hub h and retailer i
$\mathbf{Dist}_{ij}$	: Distance matrix between retailer i and retailer j
$\mathbf{Dem}_{ip}$	: Demand of retailer i
$\mathbf{Vol}_{c}$	: fractional volume of PI-container c
$\mathbf{V}_{p}$	: fractional volume of PI-box p
$\mathbf{TC}$	: Fixed unit transportation cost per kilometer
$\mathbf{C}$	: Penalty Cost for remaining space inside the PI-containers
$\mathbf{I}_{hp}$	: Inventory level at hub h for Pi-box p

Decision variables:

$$L_c = \begin{cases} 1 & \text{if PI-container } c \text{ is used} \\ 0 & \text{otherwise} \end{cases}$$

$$Y_{hic} = \begin{cases} 1 & \text{if Pi-container } c \text{ goes from hub } h \text{ to retailer } i \\ 0 & \text{otherwise} \end{cases}$$

$$X_{ijch} = \begin{cases} 1 & \text{if Pi-container } c \text{ goes from retailer } i \text{ to retailer } j \text{ starting from hub } h \\ 0 & \text{otherwise} \end{cases}$$

$$Z_{ihc} = \begin{cases} 1 & \text{if Pi-container } c \text{ goes from retailer } i \text{ to hub } h \\ 0 & \text{otherwise} \end{cases}$$

B_{pci} : Quantity of Pi-box p packed in the Pi-container c to serve retailer i
U_i : to eliminate sub tours
O_c : The occupied volume inside Pi-container$c$
R_c : filling rate of Pi-container$c$

Objective functions:

$$Z1 = \min TC \left(\sum_h \sum_i \sum_k D_{hi} \cdot Y_{hik} + \sum_h \sum_i \sum_j \sum_k \text{Dist}_{ij} \cdot X_{ijhk} + \sum_i \sum_h \sum_k D_{hi} \cdot Z_{ihk} \right) \tag{3.1}$$

This objective function represents the total transportation cost in our Physical internet network .It is composed of the distance traveled from hubs to retailers, from retailers to retailers and finally for retailers to hub.

$$Z2 = \min C \cdot \sum_c ((Vol_c \cdot L_c) - O_c/0.25) \tag{3.2}$$

This objective represents represents the cost on the remaining void in the pi-containers . This objective aims to minimize the utilization of PI-containers.This cost represents the penalty cost on the empty space associated with each 0.25 unit of volume, which is why we divide the remaining volume in the pi-container by 0.25

Constraints:

$$I \cdot \sum_i Y_{hic} \geq \sum_i \sum_j X_{ijhc} \quad \forall\, c\, \forall\, h \tag{3.3}$$

$$I \cdot \sum_i \sum_h Z_{ihc} \geq \sum_i \sum_j \sum_h X_{ijhc} \quad \forall\, c \tag{3.4}$$

$$\sum_h Y_{hit} + \sum_h \sum_j X_{jihc} = \sum_h Z_{ihc} + \sum_h \sum_j X_{ijhc} \quad \forall\, c\, \forall\, i \tag{3.5}$$

$$X_{iic} = 0 \quad \forall c \forall i \tag{3.6}$$

$$U_i - U_j + I \cdot X_{ijht} \leq I - 1 \quad \forall\, i\, \forall\, j\, \forall\, t\, \forall\, h \tag{3.7}$$

$$\sum_{c} B_{pci} = \text{Dem}_{ip} \quad \forall i, \forall p \tag{3.8}$$

$$\sum_{p}\sum_{i} B_{pci} \cdot V_p \leq Vol_c \cdot L_c \quad \forall c \tag{3.9}$$

$$\sum_{t}\sum_{i} Dem_i \cdot Y_{hit} + \sum_{t}\left(\sum_{i}\sum_{j} Dem_j \cdot X_{ijht}\right) \leq I_h \cdot Q_h \quad \forall h \tag{3.10}$$

$$Y_{hic} \leq L_c \quad \forall h \quad \forall i \quad \forall c \tag{3.11}$$

$$Z_{hic} \leq L_c \quad \forall h \forall i \forall c \tag{3.12}$$

$$X_{ijhc} \leq L_c \quad \forall h \forall j \forall i \forall c \tag{3.13}$$

$$\sum_{p} B_{pci} \leq 1000 \cdot (\sum_{h} Y_{hic} + \sum_{j}\sum_{h} X_{jihc}) \quad \forall i \forall c \tag{3.14}$$

$$\text{O}_c = \sum_{p \in p}\sum_{i \in r} V_p \cdot B_{pci} \quad \forall c \tag{3.15}$$

$$\text{R}_c = \frac{\text{O}_c}{\text{Vol}_c} \quad \forall c \tag{3.16}$$

$$\sum_{i} Y_{hit} = \sum_{i} Z_{iht} \quad \forall\, h\, \forall\, t \tag{3.17}$$

$$Q_h, X_{ijt}, Y_{hit}, Z_{iht} \in \{0, 1\} \quad \forall\, i\, \forall\, j\, \forall\, t\, \forall\, h \tag{3.18}$$

$$U_i, B_{pci} \in N \quad \forall\, i \tag{3.19}$$

$$R_c, O_c \in R \quad \forall\, i \tag{3.20}$$

Equation (3.3) and (3.4) indicate that each route must begin and terminate at a hub. The initial hub and the final hub may be identical or distinct. Equation (3.5) ensures the preservation the the flow for each retailer and guarantees that every truck entering a retailer must exit it as well. Equation (3.6) indicates that the vehicle must move from one retailer to another retailer or the end hub and can't move from a retailer to this same retailer. Equation(3.7) eliminates sub tours in each route. (3.8) states that the total demand of a retailer i for a Pi-box p can be served using different PI-containers. Equation(3.9) states that the loading quantity of PI-boxes at the starting hub constructed of multiple retailers demands should respect the truck total volume. Equation(3.10) denotes that the total loading quantity at each hub for all trucks starting their tour from this hub should respect the hub's inventory level. Equation(3.11),(3.12) and (3.13) ensures that there is no PI-container will be routed unless this PI-container is used. Equation(3.14) is forcing constraint to connect the two decision variables, B and the routing variables. (3.15) calculates the occupied volume inside the PI-container. (3.16) calculates the filling rate of a PI-container.Equation(3.17) is used for the case of classical supply chain where the starting and the ending hub must be the same.

3.2 Resolution approach

The proposed model was solved using **IBM ILOG CPLEX(version 13.8)** solver on an i5 CPU with 16GB Ram laptop for the both objectives separately:

- **Case 01**: Testing the first objective.
- **Case 02**: Testing the second objective.

Then the model was solved using **Gurobi 11.0.1** solver using python to test the multi-objective model with different priorities for both objectives:

- **Case 03**: Same priority for both objectives using :
  model.setObjectiveN(Z1, index=1, priority=1)
  model.setObjectiveN(Z2, index=2, priority=1)
- **Case 04**: Priority for the first objective :
  model.setObjectiveN(Z1, index=1, priority=2)
  model.setObjectiveN(Z2, index=2, priority=1)
- **Case 05**: Priority for the second objective :
  model.setObjectiveN(Z1, index=1, priority=1)
  model.setObjectiveN(Z2, index=2, priority=2)

The main objective of this work is to compare the model's behavior across all presented cases and evaluate the different results.

3.3 Application

3.3.1 Data

The model was evaluated using a randomly generated dataset to assess its efficiency and behavior. Four PI-box sizes were proposed: {0.25, 0.5, 0.75, 1}, and PI-container size fixed to be 2, inspired by the approach in [Fazili et al., 2017]. The demand for each type of PI-box ranged from 1 to 3 units. Distances between locations varied from 1 to 20 km. The inventory levels at hubs were also specified in terms of PI-box types, with quantities ranging from 1 to 3 units. The penalty cost for the free space in the PI-container was assumed to be 5U/ 0.25 unit of volume, and the transportation cost was assumed to be 2U/km.

Data	values
Distance	random :[1 -20] km
Retailers demand	[1 -3] PI-box for each type
Inventory levels	[1 -3] PI-box for each type
PI-container size	2
PI-box size	{0.25, 0.5, 0.75, 1}
The penalty cost	5U/ 0.25 unit of volume
Transportation cost	2 euros per kilometer

Table 3.1: Data

The model was tested under two instances presented in the table below :
The model was also tested using large instances. However, due to the complexity of the proposed model and the use of CPLEX and Gurobi solvers, solving larger instances

Scenario	Nb hubs	Nb retailers	Nb of available PI-containers
Scenario 01	3	4	4
Scenario 02	4	8	8

Table 3.2: Scenarios

proved challenging. For example, when the model was tested with 12 retailers, even after an hour and a half, the CPLEX solver still reported a gap of 100%. The results of the proposed instances are presented in the next section

3.3.2 Results

First scenario

Case	**Values**	**Nb of utilized PI-containers**	**Filling rate**
Z1	210.2	4	C1 : 75% C2 : 62.5% C3 : 50% C4 : 100%
Z2	5	3	C1 : 100% C2 : 0% C3 : 100% C4 : 87.5%
Multi-objective resolution with the same priority	Z1= 247 Z2= 5	3	C1 : 100% C2 : 0% C3 : 100% C4 : 87.5%
Multi-objective resolution with priority for the first objective	Z1= 210.2 Z2= 45	4	C1 : 62.5% C2 : 100% C3 : 50% C4 : 75%
Multi-objective resolution with priority for the second objective	Z1= 247 Z2= 5	3	C1 : 62.5% C2 : 100% C3 : 50% C4 : 75%

Table 3.3: Comparison of results for different casess

In the previous table, the values of both objective functions, the number of utilized PI-containers and their filling rate were presented. The results were compared for the five cases previously mentioned, in the first case the model was solved as a mono-objective model to optimize Z1 using cplex, same for the second case where only the second objective was optimize. In the third case the model was solved as a bi-objective model with the same priority for both objectives and it was implemented in Gurobi. In the fourth case the first objective was prioritized over the second one, and in the last case the second objective was prioritized.

From the results, we observe that the two objectives are contradictory. Minimizing the first objective (transportation costs) deteriorates the second objective (free space) and vice versa. The second objective is proportional to the number of utilized PI-containers, and using fewer PI-containers means a higher filling rate.

In the case where both objectives were considered with the same priority (third case), three PI-containers were used for Z1 = 247 and Z2 = 5. The filling rates for each container are: C1: 100%, C2: 0%, C3: 100%, C4: 87.5%. These results show a balance between the two objectives, with a compromise found to optimize both transportation costs and free space at the same time.

Analyzing further the fourth and fifth cases where priority was given to one objective over the other, we can see the impacts of the defined priorities:

- **fourth case** (priority to the first objective) : Z1 = 210.2, Z2 = 45
  Four PI-containers were used.
  Filling rates of the containers: C1: 62.5%, C2: 100%, C3: 50%, C4: 75%.
  In this case, by prioritizing the minimization of transportation costs (Z1), the number of PI-containers used increased to four, leading to an increase in Z2 to 45. The filling rates vary more widely, showing less efficient use of space.

- **Fifth case** (priority to the second objective): Z1 = 247, Z2 = 5
  Three PI-containers were used.
  Filling rates of the containers: C1: 62.5%, C2: 100%, C3: 50%, C4: 75%.
  Here, by prioritizing the minimization of free space (Z2), the solution uses three PI-containers, maintaining a lower Z2 value at the cost of a higher Z1. The filling rates suggest a more efficient use of space compared to the fourth case.

To incorporate this the results are represented graphically in the following figures: 3.1 and 3.2.

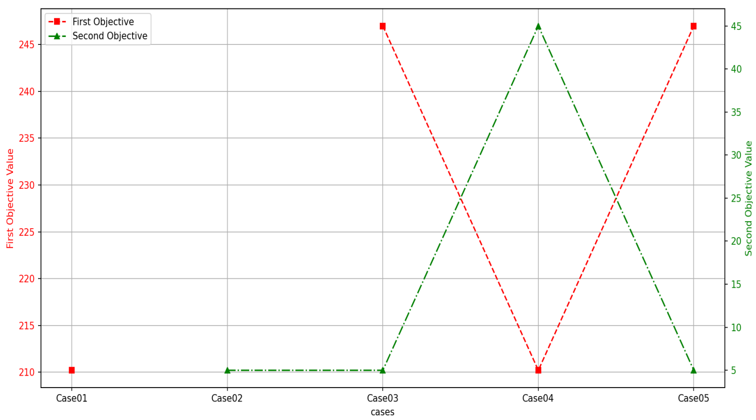

Figure 3.1: Comparison of results for different cases

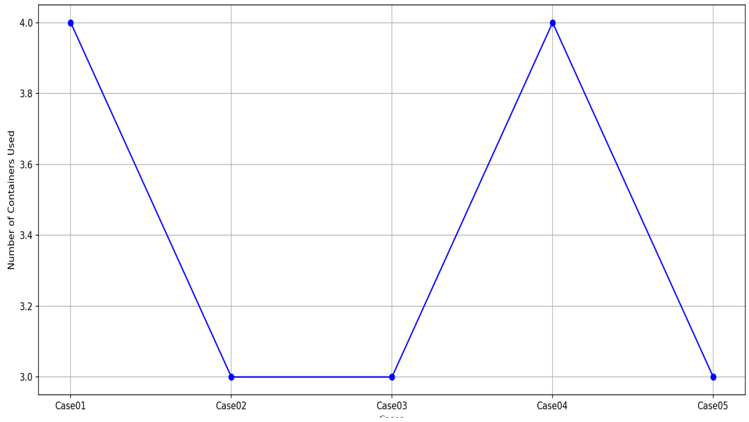

Figure 3.2: Number of used containers for all cases

3.3.3 Second scenario

The results are presumed in table 3.4
In the first case, the primary goal was to minimize transportation costs (Z1). The model used 8 PI-containers, with most of them nearly or fully utilized. This demonstrates that while transportation costs are minimized, a relatively high number of containers are needed, leading to some inefficiencies in container usage.

In the second case the focus was on minimizing free space (Z2). The model used 7 PI-containers, achieving high filling rates with almost all containers fully utilized except one, which was not used at all. This indicates a more efficient use of container space but at the potential cost of higher transportation costs.

In the third case when both objectives were given equal priority, the model again used 8 PI-containers. The filling rates were more balanced, with a slight reduction in efficiency for some containers (C6 and C7 at 62.5%). This indicates a compromise between minimizing transportation costs and optimizing container usage.

In the fourth case where the first objective (transportation costs) was prioritized yielded identical results to the third case, with 8 PI-containers and similar filling rates. This suggests that giving priority to Z1 does not significantly impact the overall balance compared to equal priority.

Finally in the last case When prioritizing the second objective (free space), the model used 7 PI-containers, resulting in a higher Z1 value (729.9) but a very low Z2 (10). This demonstrates an efficient use of space, with nearly all containers fully utilized, though at a significantly higher transportation cost.
The comparison of results between different cases is represented in the following figure 3.3, and the number of utilized halfPI-containers in figure 3.4

Case	Values	Nb of utilized PI-containers	Filling rate
Z1	551,4	8	C1 : 100% C2 : 100% C3 : 75% C4 : 87,5% C5 : 100% C6 : 100% C7 : 75% C8 : 87,5%
Z2	10	7	C1 : 100% C2 : 100% C3 : 100% C4 : 100% C5 : 0% (NU) C6 : 100% C7 : 100% C8 : 75%
Multi-objective resolution with the same priority	Z1= 551,4 Z2= 50	8	C1 : 100% C2 : 100% C3 : 75% C2 : 87,5% C3 : 100% C2 : 62,5% C3 : 62,5% C4 : 87,5%
Multi-objective resolution with the priority for the first objective	Z1= 551,4 Z2= 50	8	C1 : 100% C2 : 100% C3 : 75% C2 : 87,5% C3 : 100% C2 : 62,5% C3 : 62,5% C4 : 87,5%
Multi-objective resolution with priority for the second objective	Z1= 729,9 Z2= 10	7	C1 : 100% C2 : 100% C3 : 100% C4 : 100% C5 : 0% (NU) C6 : 100% C7 : 100% C8 : 75%

Table 3.4: Summary of PI-container utilization and filling rates for different scenarios

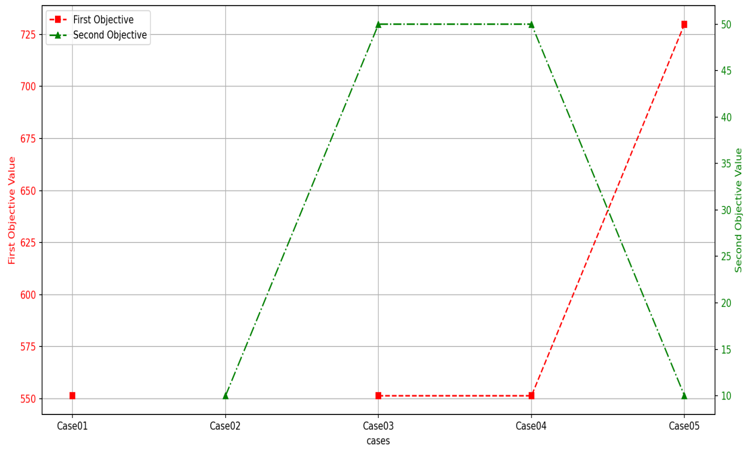

Figure 3.3: Comparison of results for different cases

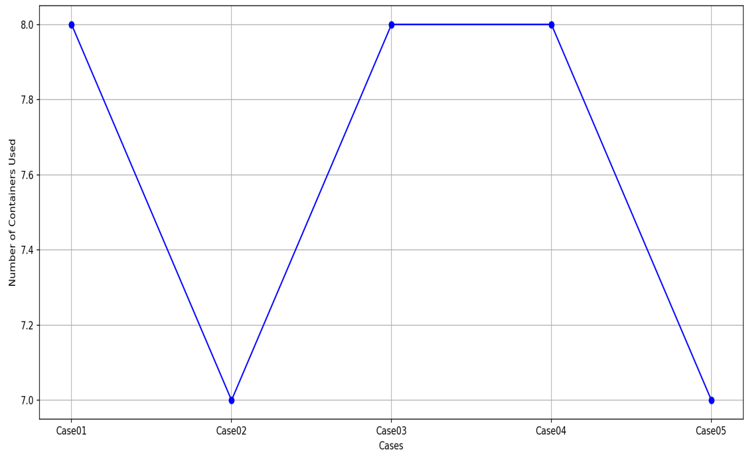

Figure 3.4: Number of used containers for all cases

3.4 Multi-period model

3.4.1 Problem description

In the proposed model, we are working on a vehicle routing problem in a physical internet context. This problem involves operational routing of vehicles to efficiently meet the demands of our retailers expressed in term of PI-boxes while trying to minimize the free space inside the PI-containers for different time periods.
The idea of PI-boxes that represents another aspect of PI principles was inspired from [Fazili et al., 2017] where they have introduced a multi-phase model. They have considered that demands are expressed in terms of PI-boxes with different sizes(fractional volumes) that will be transported using a set of PI-containers with a maximum capacity(fractional volume).
The main objective is to minimize at the same time the transportation costs and the empty space inside the PI-containers. The proposed model presents also the number of utilized PI-containers and their filling rates as decision variables to compare how the system will reacts under different cases.

Given a set of potential Hubs H where:$\{ h = 1, \dots, H \}$ that are located to serve a set of retailers R: $\{ i = 1, \dots, R \}$ with different demands expressed in terms of PI-boxes

P: { p = 1, . . . , P } using a set of PI-containers C: { c = 1, . . . , C } for a set of time periods T:{ t = 1, . . . , T }

3.4.2 Assumptions

The proposed model addresses the vehicle routing problem within the physical internet framework. Before we dive into our model, it's important to mention the assumptions guiding our approach:

- Demands are expressed in term of PI-box, that will be transported in PI-containers.
- PI-containers and PI-boxes have fractional volumes based on [Fazili et al., 2017] works. PI-containers have the same fractional size of 2, and four different fractional sizes for the PI-boxes of {0.25, 0.5, 0.75, 1}.
- There is a penalty cost associated with the remaining free space in the PI-containers.
- Multiple periods are presumed to be set.
- A retailer's demand can be satisfied using different PI-containers. Each retailer can be visited different times in a route.
- Hubs have an inventory level that must be respected.
- Hubs can share their different resources: trucks and drivers.
- The starting and ending hubs of a truck can be the same or different. The truck returns to the closet hub in the route.

3.4.3 Mathematic formulation

Notations

$\mathbf{H}$	: Set of PI-Hubs
$\mathbf{I}$	: Set of retailers
$\mathbf{C}$	: Set of PI-containers
$\mathbf{P}$	: Set of PI-boxes
$\mathbf{T}$	: Set of Periods
$\mathbf{D}_{hi}$	: Distance matrix between hub h and retailer i
$\mathbf{Dist}_{ij}$	: Distance matrix between retailer i and retailer j
$\mathbf{Dem}_{ipt}$	: Demand of retailer i for PI-box p in period t
$\mathbf{Vol}_c$	: fractional volume of PI-container c
$\mathbf{V}_p$	: fractional volume of PI-box p
$\mathbf{TC}$	: Fixed unit transportation cost per kilometer
$\mathbf{C}$	: Cost
$\mathbf{I}_{hpt}$	: Inventory level at hub h for Pi-box p in period t

Decision variables:

$$L_{ct} = \begin{cases} 1 & \text{if Pi-container } c \text{ is used in the period} t \\ 0 & \text{otherwise} \end{cases}$$

$$Y_{hict} = \begin{cases} 1 & \text{if Pi-container } c \text{ goes from hub } h \text{ to retailer } i \text{ in the period } t \\ 0 & \text{otherwise} \end{cases}$$

$$X_{ijcht} = \begin{cases} 1 & \text{if Pi-container } c \text{ goes from retailer } i \text{ to retailer } j \text{ starting from hub } h \text{ in the period } t \\ 0 & \text{otherwise} \end{cases}$$

$$Z_{ihct} = \begin{cases} 1 & \text{if Pi-container } c \text{ goes from retailer } i \text{ to hub } h \text{ in the period } t \\ 0 & \text{otherwise} \end{cases}$$

B_{pcit} : Quantity of Pi-box p packed in the PI-container c to serve retailer i in the period t

U_{it} : to eliminate sub tours

O_{ct} : The occupied volume inside Pi-container$c$in the period t

R_{ct} : filling rate of Pi-container$c$in the period t

Objective functions:

$$\mathbf{Z1} = \min TC \left(\sum_h \sum_i \sum_c \sum_t D_{hi} \cdot Y_{hict} + \sum_h \sum_i \sum_j \sum_c \sum_t \text{Dist}_{ij} \cdot X_{ijhct} + \sum_i \sum_h \sum_t \sum_k D_{hi} \cdot Z_{ihct} \right) \tag{3.21}$$

This objective function represents the total transportation cost in our Physical internet network .It is composed of the distance traveled from hubs to retailers, from retailers to retailers and finally for retailers to hub for all the periods.

$$\mathbf{Z2} = \min C \cdot \sum_c \sum_t ((Vol_c \cdot L_{ct}) - O_{ct}/0.25) \tag{3.22}$$

This objective represents represents the cost on the remaining void in the pi-containers . This objective aims to minimize the utilization of PI-containers.This cost represents the penalty cost on the empty space associated with each 0.25 unit of volume, which is why we divide the remaining volume in the pi-container by 0.25.

Constraints:

$$I \cdot \sum_i Y_{hict} \geq \sum_i \sum_j X_{ijhct} \quad \forall\, c \,\forall\, h \forall\, t \tag{3.23}$$

$$I \cdot \sum_i \sum_h Z_{ihct} \geq \sum_i \sum_j \sum_h X_{ijhct} \quad \forall\, c \forall\, t \tag{3.24}$$

$$\sum_h Y_{hict} + \sum_h \sum_j X_{jihct} = \sum_h Z_{ihct} + \sum_h \sum_j X_{ijhct} \quad \forall\, c \,\forall\, i \forall\, t \tag{3.25}$$

$$X_{iict} = 0 \quad \forall c \forall i \forall\, t \tag{3.26}$$

$$U_{it} - U_{jt} + I \cdot X_{ijhct} \leq I - 1 \quad \forall\, i \,\forall\, j \,\forall\, c \,\forall\, h \forall\, t \tag{3.27}$$

$$\sum_{c} B_{pcit} = \text{Dem}_{ipt} \quad \forall i \forall p \forall\, t \tag{3.28}$$

$$\sum_{p} \sum_{i} B_{pcit} \cdot V_p \leq Vol_c \cdot L_{ct} \quad \forall c \forall\, t \tag{3.29}$$

$$\sum_{c} \sum_{i} Dem_{ipt} \cdot Y_{hict} + \sum_{c} \left(\sum_{i} \sum_{j} Dem_j \cdot X_{ijhct} \right) \leq I_{hpt} \quad \forall h \forall p \forall\, t \tag{3.30}$$

$$Y_{hict} \leq L_{ct} \quad \forall h \quad \forall i \quad \forall c \forall t \tag{3.31}$$

$$Z_{hict} \leq L_{ct} \quad \forall h \forall i \forall c \forall t \tag{3.32}$$

$$X_{ijhct} \leq L_{ct} \quad \forall h \forall j \forall i \forall c \forall t \tag{3.33}$$

$$\sum_{p} B_{pcit} \leq 1000 \cdot (\sum_{h} Y_{hict} + \sum_{j} \sum_{h} X_{jihct}) \quad \forall i \forall c \forall t \tag{3.34}$$

$$\text{O}_{ct} = \sum_{p} \sum_{i} V_p \cdot B_{pcit} \quad \forall c \forall t \tag{3.35}$$

$$\text{R}_{ct} = (\frac{\text{O}_{ct}}{\text{Vol}_c}) * 100\% \quad \forall c \forall t \tag{3.36}$$

$$\sum_{i} Y_{hict} = \sum_{i} Z_{ihct} \quad \forall\, h \,\forall c \forall\, t \tag{3.37}$$

$$X_{ijhct}, Y_{hict}, Z_{ihct} \in \{0, 1\} \quad \forall\, i \,\forall\, j \,\forall\, c \,\forall\, h \forall t \tag{3.38}$$

$$U_i t, B_{pcit} \in N \quad \forall\, i \forall t \tag{3.39}$$

$$R_{ct}, O_{ct} \in R \quad \forall c \forall t \tag{3.40}$$

The following constraints are applicable for all time periods:
Equation (3.23) and (3.24) indicate that each route must begin and terminate at a hub. The initial hub and the final hub may be identical or distinct. Equation (3.25) ensures the preservation the the flow for each retailer and guarantees that every truck entering a retailer must exit it as well. Equation (3.26) indicates that the vehicle must move from one retailer to another retailer or the end hub and can't move from a retailer to this same retailer. Equation(3.27) eliminates sub tours in each route. (3.28) states that the total demand of a retailer i for a Pi-box p can be served using different PI-containers. Equation(3.29) states that the loading quantity of PI-boxes at the starting hub constructed of multiple retailers demands should respect the truck total volume. Equation(3.30) denotes that the total loading quantity at each hub for all trucks starting

their tour from this hub should respect the hub's inventory level. Equation(3.31),(3.32) and (3.33) ensures that there is no PI-container will be routed unless this PI-container is used. Equation(3.34) is forcing constraint to connect the two decision variables, B and the routing variables. (3.35) calculates the occupied volume inside the PI-container. (3.36) calculates the filling rate of a PI-container.Equation(3.37) is used for the case of classical supply chain where the starting and the ending hub must be the same.

3.5 Application

3.5.1 Data

The model was evaluated using a randomly generated dataset to assess its efficiency and behavior for five time periods. Four PI-box sizes were proposed: {0.25, 0.5, 0.75, 1}, and PI-container size fixed to be 2, inspired by the approach in [Fazili et al., 2017]. The demand for each type of PI-box ranged from 1 to 3 units. Distances between locations varied from 1 to 20 km. The inventory levels at hubs were also specified in terms of PI-box types, with quantities ranging from 1 to 3 units for each time periods. The penalty cost for the free space in the PI-container was assumed to be 5U/ 0.25 unit of volume, and the transportation cost was assumed to be 2U/km.

Data	values
Distance	random :[1 -20] km
Retailers demand	[1 -3] PI-box for each type for all periods
Inventory levels	[1 -3] PI-box for each type for all periods
PI-container size	2
PI-box size	{0.25, 0.5, 0.75, 1}
The penalty cost	5U/ 0.25 unit of volume
Transportation cost	2 euros per kilometer
Periods	5

Table 3.5: Data

The model was tested under one data instance presented in the table below :

Scenario	Nb hubs	Nb retailers	Nb of available PI-containers
Scenario 01	3	4	4

Table 3.6: Scenarios

The model was also tested using large instances. However, due to the complexity of the proposed model and the use of CPLEX and Gurobi solvers, solving larger instances proved challenging. For example, when the model was tested with 8 retailers, even after an hour and a half, the CPLEX solver still reported a gap of 100%. The results of the proposed instances are presented in the next section.

3.5.2 Results

Case	Values	Nb of utilized PI-containers
Z1	1060,8	T1 : 4 T2 : 4 T3 : 3 T4 : 4 T5 : 4
Z2	120	T1 : 3 T2 : 4 T3 : 3 T4 : 3 T5 : 4
Multi-objective resolution with the same priority	Z1= 1105,6 Z2= 120	T1 : 3 T2 : 4 T3 : 3 T4 : 4 T5 : 3
Multi-objective resolution with priority for the first objective	Z1= 1060,8 Z2= 200	T1 : 4 T2 : 4 T3 : 4 T4 : 4 T5 : 4
Multi-objective resolution with priority for the second objective	Z1= 1105,6 Z2= 120	T1 : 3 T2 : 4 T3 : 3 T4 : 4 T5 : 3

Table 3.7: Summary of PI-container utilization and objective functions values

Filling rate for all the cases

	C1	C2	C3	C4
P1	100%	0%	100%	87.5%
P2	50%	75%	100%	62.5%
P3	100%	100%	0%	87.5%
P4	50%	100%	100%	62.5%
P5	100%	100%	0%	87.5%

Table 3.8: Third case

	C1	C2	C3	C4
P1	50%	75%	62.5%	100%
P2	62.5%	100%	50%	75%
P3	75%	0%	62.5%	87.5%
P4	50%	100%	75%	62.5%
P5	50%	100%	100%	62.5%

Table 3.9: Fifth case

	C1	C2	C3	C4
P1	50%	62.5%	100%	75%
P2	75%	50%	100%	62.5%
P3	75%	87.5%	62.5%	0%
P4	75%	100%	62.5%	50%
P5	100%	100%	50%	62.5%

Table 3.10: First case

	C1	C2	C3	C4
P1	50%	62.5%	100%	75%
P2	75%	50%	100%	62.5%
P3	75%	87.5%	62.5%	0%
P4	75%	100%	62.5%	50%
P5	100%	100%	50%	62.5%

Table 3.11: Fourth case

	C1	C2	C3	C4
P1	87.5%	0%	100%	100%
P2	62.5%	75%	50%	100%
P3	87.5%	0%	75%	62.5%
P4	87.5%	100%	100%	0%
P5	62.5%	100%	100%	50%

Table 3.12: Second case

In the first case, the primary objective was to minimize transportation costs Z1. The model utilized for most of periods 4 PI-containers (T1: 4, T2: 4, T3: 3, T4: 4, T5: 4), with most containers being nearly or fully utilized. This indicates an effective reduction in transportation costs but also highlights the need for a relatively high number of containers, which may lead to inefficiencies in container usage.

In the second case, the emphasis shifted to minimizing free space Z2. Here, the model utilized mostly three PI-containers (T1: 3, T2: 4, T3: 3, T4: 3, T5: 4), achieving high filling rates where almost all containers were fully utilized except one that remained unused for three time periods. This points to a more efficient use of container space, potentially at the expense of increased transportation costs.

In the third case, where both objectives were given equal priority (Z1: 1105.6, Z2: 120). The filling rates were more balanced across containers, although some containers showed slightly reduced efficiency. This scenario represents a compromise between minimizing transportation costs and optimizing container usage.

In the fourth case, prioritizing the first objective (transportation costs) resulted in outcomes similar to the first case with comparable filling rates, prioritizing Z1 did not significantly alter the overall balance compared to equal priority.

Finally, in the fifth case where the second objective (free space) was prioritized This configuration achieved efficient space utilization with nearly all containers fully utilized for all time periods, but at the cost of significantly higher transportation expenses.

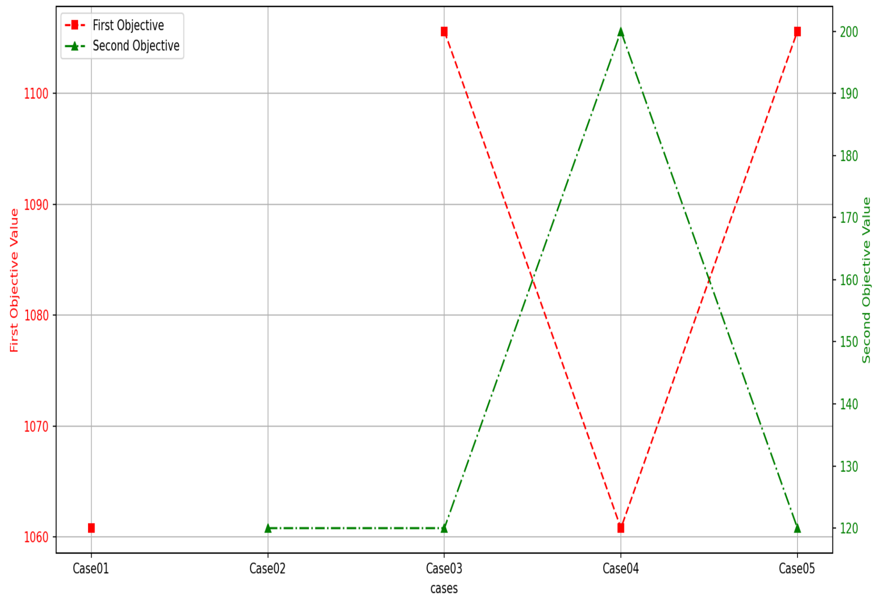

Figure 3.5: Comparison of results for different cases

Conclusion

This chapter has explored the vehicle routing problem (VRP) within the context of the Physical Internet, presenting both single-period and multi-period models aimed at optimizing logistics operations. The findings indicate that applying PI principles, such as standardized, modular containers and dynamic routing, can significantly enhance the efficiency of vehicle routes, reduce transportation costs, and minimize unused space within PI-containers.

The practical applications and results discussed in this chapter underscore the potential for the Physical Internet to revolutionize the logistics industry by promoting more efficient, sustainable, and resilient supply chain operations. These insights lay a solid foundation for future research and implementation of PI-based routing strategies, advancing the broader adoption and realization of the Physical Internet's benefits.

General conclusion

This thesis investigates the transformative potential of the Physical Internet (PI) in modern logistics, focusing on the Vehicle Routing Problem (VRP) and the innovative use of PI-boxes and PI-containers. The primary goals are to reduce transportation costs and optimize space utilization within containers.

By integrating PI principles into VRP, the research demonstrates notable improvements in logistics efficiency. The use of standardized PI-containers streamlines the movement of goods, leading to cost savings and better operational efficiency. The study employs dynamic routing algorithms tailored to the PI framework, achieving optimal routing solutions that balance cost reduction and space optimization.

Key findings underscore the effectiveness of PI-containers in enhancing logistics operations, standardizing processes, and contributing to significant cost savings. Additionally, the use of PI-specific routing algorithms plays a crucial role in optimizing transportation routes and maximizing container space utilization.

In summary, this research showcases how the Physical Internet, through the strategic use of PI-boxes, PI-containers, and advanced routing algorithms, can revolutionize logistics by making supply chains more efficient and sustainable.

List of Figures

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