University of the Aegean
School of Business
Department of Financial and Management Engineering

Network protocols for the Physical Internet

Konstantinos Mertzanis
Supervisor: Dr. Maria A. Lambrou

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University of the Aegean
School of Business
Department of Financial and Management Engineering

Diploma thesis submitted by

Konstantinos Mertzanis

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Diploma Thesis Committee:

Dr. Maria A. Lambrou, Associate Professor of e-Business (Supervisor)
Department of Shipping, Trade and Transport

Dr. Anastasia Constantelou, Associate Professor of Innovation Management
Department of Financial and Management Engineering

Dr. Konstantinos Panou, Associate Professor of Transportation
Department of Shipping, Trade and Transport

Chios,
September 2016
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Abstract

The way physical objects are currently transported, handled, stored, realized, supplied and used throughout the world is not sustainable economically, environmentally and socially. The Physical Internet is a new, sustainable paradigm introducing an open, global logistics system founded on physical, digital and operational interconnectivity, through interfaces, protocols and the encapsulation of goods. This diploma thesis aims to contribute to the realization of the Physical Internet as a means to improve the sustainability of logistics. In that light, both the Physical and the Digital Internet are explored, analyzed and subsequently compared. In accordance with the results of this endeavor, a reference model is introduced, providing a conceptual framework. An implementation of this reference model is also designed in the form of three-layered protocol stack.

Περίληψη

Ο τρόπος με τον οποίο τα φυσικά αντικείμενα κατασκευάζονται, μεταφέρονται, αποθηκεύονται, διανέμονται και χρησιμοποιούνται ανά τον κόσμο δεν είναι βιώσιμος οικονομικά, περιβαλλοντικά και κοινωνικά. Το Φυσικό Διαδίκτυο είναι ένα νέο, βιώσιμο υπόδειγμα που εισάγει ένα ανοικτό, παγκόσμιο σύστημα μεταφοράς και αποθήκευσης το οποίο βασίζεται στη φυσική, ψηφιακή και επιχειρησιακή διασυνδεσιμότητα, μέσα από διεπαφές, πρωτόκολλα και την ενθυλάκωση εμπορευμάτων. Αυτή η διπλωματική εργασία στοχεύει στο να συνεισφέρει στην πραγματοποίηση του Φυσικού Διαδικτύου, ως ένα μέσο για τη βελτίωση της βιωσιμότητας του κλάδου. Υπό το πρίσμα αυτό, τόσο το Φυσικό όσο και το Ψηφιακό Διαδίκτυο ερευνώνται, αναλύονται και στη συνέχεια συγκρίνονται. Με βάση τα αποτελέσματα αυτής της προσπάθειας, ένα μοντέλο αναφοράς εισάγεται, παρέχοντας ένα εννοιολογικό πλαίσιο. Μια εφαρμογή αυτού του μοντέλου αναφοράς σχεδιάζεται επίσης, υπό τη μορφή μίας στοιχέιας πρωτοκόλλων τριών επιπέδων.
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<th>Definition</th>
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<tr>
<td>ARPANET</td>
<td>Advanced Research Projects Agency Network</td>
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<tr>
<td>ALICE</td>
<td>Alliance for Logistics Innovation through Collaboration in Europe</td>
</tr>
<tr>
<td>CELDi</td>
<td>Center for Excellence in Logistics and Distribution</td>
</tr>
<tr>
<td>COMCIS</td>
<td>Collaborative information services for container management</td>
</tr>
<tr>
<td>CORE</td>
<td>Consistently Optimised Resilient Secure Global Supply-Chains</td>
</tr>
<tr>
<td>DSL</td>
<td>Digital Subscriber Line</td>
</tr>
<tr>
<td>DSLAM</td>
<td>Digital Subscriber Line Access Multiplexer</td>
</tr>
<tr>
<td>DSN</td>
<td>Domain Name System</td>
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<tr>
<td>EV</td>
<td>Electric Vehicle</td>
</tr>
<tr>
<td>EPCIS</td>
<td>Electronic Product Code Information Services</td>
</tr>
<tr>
<td>ETA</td>
<td>Estimated Time of Arrival</td>
</tr>
<tr>
<td>ETP</td>
<td>European Technology Platform</td>
</tr>
<tr>
<td>EU</td>
<td>European Union</td>
</tr>
<tr>
<td>FMCG</td>
<td>Fast-Moving Consumer Goods</td>
</tr>
<tr>
<td>FTTH</td>
<td>Fiber to the Home</td>
</tr>
<tr>
<td>FREVUE</td>
<td>Freight Electric Vehicles in Urban Europe</td>
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<tr>
<td>GPS</td>
<td>Global Positioning System</td>
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<tr>
<td>GDP</td>
<td>Gross Domestic Product</td>
</tr>
<tr>
<td>HTTP</td>
<td>Hypertext Transfer Protocol</td>
</tr>
<tr>
<td>ICT</td>
<td>Information and Communications Technology</td>
</tr>
<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers</td>
</tr>
<tr>
<td>iCargo</td>
<td>Operations</td>
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<tr>
<td>ISO</td>
<td>International Organization for Standardization</td>
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<tr>
<td>ICMP</td>
<td>Internet Control Message Protocol</td>
</tr>
<tr>
<td>Acronym</td>
<td>Full Form</td>
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<tr>
<td>IXP</td>
<td>Internet eXchange Point</td>
</tr>
<tr>
<td>IoT</td>
<td>Internet of Things</td>
</tr>
<tr>
<td>IP</td>
<td>Internet Protocol</td>
</tr>
<tr>
<td>ISP</td>
<td>Internet Service Provider</td>
</tr>
<tr>
<td>LAN</td>
<td>Local Area Network</td>
</tr>
<tr>
<td>MAN</td>
<td>Metropolitan Area Network</td>
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<tr>
<td>MODULUSHCA</td>
<td>Modular Logistics Units in SHared co-Modal networks</td>
</tr>
<tr>
<td>OSI</td>
<td>Open Systems Interconnection</td>
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<tr>
<td>OTC</td>
<td>Open Tracing Container</td>
</tr>
<tr>
<td>PAN</td>
<td>Personal Area Network</td>
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<tr>
<td>PI or π</td>
<td>Physical Internet</td>
</tr>
<tr>
<td>POP</td>
<td>Point of Presence</td>
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<tr>
<td>PREDIT</td>
<td>Programme de recherche et d'innovation dans les transports terrestres</td>
</tr>
<tr>
<td>RFID</td>
<td>Radio Frequency IDentification</td>
</tr>
<tr>
<td>RTP</td>
<td>Real-time Transport Protocol</td>
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<tr>
<td>RORO</td>
<td>Roll-on/roll-off</td>
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<tr>
<td>FP7</td>
<td>seventh Framework Programme</td>
</tr>
<tr>
<td>SMTP</td>
<td>Simple Mail Transfer Protocol</td>
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<tr>
<td>SONET</td>
<td>Synchronous Optical Networking</td>
</tr>
<tr>
<td>TIGER</td>
<td>Territorial Impact of Globalization for Europe and its Regions</td>
</tr>
<tr>
<td>TCP</td>
<td>Transmission Control Protocol</td>
</tr>
<tr>
<td>TEU</td>
<td>Twenty-foot Equivalent Unit</td>
</tr>
<tr>
<td>UDP</td>
<td>User Datagram Protocol</td>
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<tr>
<td>VPN</td>
<td>Virtual Private Network</td>
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<tr>
<td>WAN</td>
<td>Wide Area Network</td>
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Chapter 1. Introduction

The way physical objects are currently transported, handled, stored, realized, supplied and used throughout the world is not sustainable economically, environmentally and socially. Consequently, a three-pronged goal emerges. From an economic perspective, the goal is to unlock highly significant gains throughout the supply chain. From an environmental perspective, the goal is to reduce, by an order of magnitude, the energy consumption and the ecological footprint associated with the supply chain. From a societal perspective, the goal is to improve the quality of life of the workers directly involved in the supply chain, while making objects and functionalities more accessible (Montreuil, 2011).

The Physical Internet (PI or π) is a new paradigm that has the potential of achieving this objective by introducing an open global logistics system founded on physical, digital, and operational interconnectivity, through interfaces, protocols and the encapsulation of goods (Lounès & Montreuil, 2011; Montreuil, et al., 2012).

To bring about the Physical Internet, an open internetwork of compatible hubs is needed as a foundation. Packets moving over this internetwork belong to many different parties, enabling full horizontal and vertical collaboration; but the secure handling of both information and packets is becoming increasingly challenging. Shipments are optimized for the whole internetwork, requiring constant planning for the optimal capacity use of transport and warehousing. In order to reach the necessary level of interoperability, a modular logistic units system has to be designed. Finally, the emerging opportunities and challenges are expected to stimulate innovative business models (ETP ALICE, 2014; Montreuil, 2011).

The present diploma thesis aims to contribute towards the realization of the Physical Internet, as a means to improve the sustainability of logistics. In that light, both the Physical and the Digital Internet are explored, analyzed and subsequently compared. This venture produces some early insights about the Physical Internet, its emerging architecture and the potential for transposition of concepts between the two paradigms.

These insights are subsequently incorporated into the design of a reference model. This reference model defines three abstraction layers, breaking down the larger problem of end-to-end shipment optimization in the Physical Internet into three smaller
problems. The first layer describes a packing problem while the second and the third describe two distinct, capacitated vehicle routing problems regarding the routing in the internetwork of hubs and the last mile delivery, respectively.

In spite of the uncertainty regarding the details of the new paradigm and the absence of data that could enable simulation based benchmarking, an early implementation of the reference model is proposed. It is formed as a three-layered protocol stack, consisting of the containerization, routing and delivery protocols. The containerization protocol solves the packing problem through an integer programming approach, enfolded in a recursive greedy algorithm. The routing protocol solves the first capacitated vehicle routing problem through a dynamic programming approach enhanced by a euclidean distance heuristic, partially based on the widely used A* algorithm (Fu, et al., 2006). Finally, the delivery protocol follows an integer programming approach.
Chapter 2. Computer Networks and the Digital Internet

In this chapter we will explore the current architecture of the Internet and the hardware and software that allow it to function. To do so, a broad overview of computer networks is initially presented, gradually adding layers of complexity until the Internet, in its present form, has been overall explained. Emphasis has been given to the aspects that will be relevant later in this body of work. To avoid confusion between the Internet and the proposed Physical Internet, the former will hereafter be referred to as the Digital Internet.

This chapter is primarily based on the introduction of the book “Computer Networks” by Andrew S. Tanenbaum and David J. Wetherall (2011), loosely following it except for points where a departure was deemed necessary.

2.1 Introduction to Computer Networks

A computer network is a collection of autonomous computers interconnected by a single technology. Two computers are interconnected if they are able to exchange information. This connection can be established in a variety of ways, including copper wires, fiber optics, microwaves, infrared and communication satellites.

Computer networks are distinct from distributed systems, collections of independent computers that appear to their users as coherent systems. The autonomous computers of a network do not act coherently and may have different hardware or operation systems. This lack of coherence can cripple their effective use. The most common way to address this issue is via a layer of software on top of the operating system. This software, called middleware, is responsible for implementing a single model or paradigm to present to the users. In effect, the resulting software system, build on top of a network, is a distributed system.

2.2 Reasons for Computer Networking

There are many reasons why the interconnection of autonomous machines may be desirable. The relative importance of these reasons is not universal; it is rather the result
of various factors such as the historical and political context, the orientation of the network’s use and the industry in which the network is deployed. However, resource sharing is arguably the primary reason for the creation of a computer network.

The shared resources might be physical objects, such as printers shared by multiple employees or families. Resource sharing, however, can be much more complex than the mere common use of office equipment. Clouds, for instance, are large pools of easily usable and accessible virtualized resources such as hardware, development platforms and/or services. In this way computing resources, such as storing and processing capacity, can be dynamically reconfigured to adjust to a variable load, allowing optimal resource utilization (Vaquero, et al., 2009).

Although sharing equipment and services is very cost effective, the most important shared resource is usually information. The majority of modern companies, regardless of size, are vitally dependent on computerized information, such as customer records, tax information, financial statements, product information and inventories. Allowing authorized employees to have instant remote access to this information and documents is essential for a successful company. Of course, home users also need the internet to access remotely information on a vast spectrum of subjects.

In the simplest of terms, to share information, an information system is created, consisting of one or more databases, containing useful information, that are connected to a number of machines, operated by people who need remote access to the data. In this model, the data is stored on powerful computers called servers. Often these are centrally housed and maintained by a system administrator. In contrast, the users have simpler machines, called clients, on their desks, with which they access remote data, for example, to include in spreadsheets they are constructing. The client and server machines are connected by a network. This whole arrangement is called the client-server model and it is widely used and forms the basis of much network usage.

A second reason for setting up a computer network has to do with people rather than information or computers. A computer network can provide a powerful communication medium, both in professional and non-professional context. Most companies and households in the developed world are using email, consisting an important part of daily communication. Instant messaging and multi-person messaging
services are increasingly used by the public, especially the youth, making their use also important for businesses. Instant messaging is now present inside companies making communication inside them much faster and multi-person messaging services, like Twitter, are used to communicate about new products, discounts etc. (Muller, et al., 2003; Heller Baird & Parasnis, 2011).

Other, richer forms of communication are also made possible by computer networks. Technologies such as Voice over IP enable telephone calls to be carried by computer networks. Video is often added to audio so that people at distant locations can see and hear each other. This technique has been proven to be an important tool for eliminating the cost and time previously devoted to travel. Desktop sharing lets remote workers see and interact with a graphical computer screen. This makes it easy for two or more people who work far apart to read and write a shared blackboard or write a report together. A change to an online document can be seen immediately, instead of waiting several days for a letter. The above mentioned techniques make cooperation among far-flung groups of people easy where it previously had been impossible. Yet, there are even more ambitious forms of remote coordination such as telemedicine, the remote monitoring of patients, starting to be used and may become increasingly important.

A third reason, for many companies and their customers, is doing business electronically. This model is called e-commerce and it has grown rapidly in recent years. Airlines, bookstores, and other retailers have discovered that many customers like the convenience of shopping from home. Consequently, many companies provide catalogs of their goods and services online and take orders online. Manufacturers of automobiles, aircraft, and computers, among others, buy subsystems from a variety of suppliers and then assemble the parts. Using computer networks, manufacturers can place orders electronically as needed. This reduces the need for large inventories and enhances efficiency.

A fourth reason is pervasive computing. Pervasive devices and services abound permeating and becoming part of the private and professional lives for many, having a transformative effect on the development of the modern social and business landscape by interlinking the cyber and physical worlds. By exploiting these devices and various technologies, information about physical reality is seamlessly transferred into the cyber
world where it is elaborated to adapt cyber applications and services to the physical context, and thus possibly modifying/adapting the physical world itself through actuators (Conti, et al., 2012).

One of these technologies is Radio Frequency IDentification (RFID). It enables identification from a distance, and unlike earlier bar-code technology, it does so without requiring a line of sight (Finkenzeller, 2010). RFID tags support a larger set of unique IDs than bar codes and can incorporate additional data such as manufacturer, product type, and even measure environmental factors such as temperature. Furthermore, RFID systems can discern many different tags located in the same general area without human assistance (Want, 2006). The application of RFID technology in logistics operations and supply chain management is particularly important (Lin & Ho, 2009). This technology is one of the main drivers towards the Internet of Things (IoT) (ITU, 2005), an interesting paradigm that could be key to the implementation of the Physical Internet.

Computers can be connected for many other reasons, but computer networks, like other era-defining technologies, have also brought about unsolved ethical, political and social issues. Network neutrality, security and privacy are just few of them. Although the present diploma thesis will not attempt to examine in depth or solve such issues, it is claimed that groundbreaking changes, like the ones proposed later in this body of work, may impact on the social, political and ethical spheres in unexpected ways.

2.3 Network Hardware

There is no generally accepted taxonomy into which all computer networks fit regarding their hardware, but two dimensions stand out as important: transmission technology and scale. Both will be presented in this section.

Transmission technologies

Two types of transmission technologies are currently in wide use: point-to-point links and broadcast links.

Point-to-point links connect two machines. For a message, used here in a generic way, to go from the source to the destination on a network made up of point-to-point
links, it will have to pass from intermediate machines. Usually there are many possible routes, so defining the best ones is crucial. Point-to-point transmission from one sender to one receiver is sometimes called unicasting.

In contrast, on a **broadcast network**, the communication channel is shared by all the machines on the network; messages sent by any machine are received by all the others. An address field within each message specifies the intended recipient. When a message is received, a machine checks if the intended address matches its own. If yes, the machine accepts the message; if not, the message is ignored. A broadcast network is usually wireless and its coverage region depends on the transmitting machine and the channel. It is also usual that broadcast systems allow for the addressing of a message to all destinations by using a special code in the address field. This mode of operation is called broadcasting. Finally, some broadcast systems also support transmission to a subset of the machines, which known as multicasting.

*Network scale*

The other major criterion for classifying networks is scale. Different scales favor the use of different technologies, making distance an important classification metric.

A **Personal Area Network (PAN)** allows communication over the range of a person. A common example is the connection between a computer and its peripherals. This connection can be establish either through a wired or a wireless network, such as Bluetooth. In cases like this one, the networks normally use the master-slave paradigm, where the computer is the master controlling the behavior of the other devices.

A **Local Area Network (LAN)** is confined to a limited space, such as a building, and is usually privately owned (Donahue, 2011).

In the case of wireless LANs every computer has a radio modem and an antenna that it uses to communicate. Usually, each computer communicates with a device called access point or wireless router that relays messages between the wireless computers and also between them and other networks. The standard for this setup is called IEEE 802.11, but it is popularly known as WiFi.

Wired LANs normally use copper wires or optical fiber and perform much better than their wireless counterparts, running at much higher speeds and making fewer
mistakes. The most prevalent type of wired LAN is IEEE 802.3, popularly called Ethernet. In the case of switched Ethernet, each computer “speaks” the Ethernet protocol and connects to a switch with a point-to-point link. A switch relays messages between computers that are attached to it, using the address in each message to determine which computer to send it to. To achieve that, every switch has multiple ports each of which can connect to one computer or another switch.

A **MAN Metropolitan Area Network (MAN)** connects LANs and/or buildings in an area that is larger than a campus, within a metropolitan area (Donahue, 2011).

A **Wide Area Network (WAN)** spans a large geographical area, often a country or continent and is usually run by a third party provider.

To understand the design of a WAN let’s suppose that some computers, known as hosts, are connected, despite being geographically dispersed. These hosts, or even entire LANs, exchange messages carried by the rest of the network that connects them, which is called the communication subnet, or just subnet. In most WANs, the subnet consists of two distinct components: transmission lines and switching elements. Transmission lines are made of copper wire, optical fiber, or radio links and move bits between machines. Usually, they are leased from a telecommunications company. **Switching elements**, also known as **switches**, are specialized machines connecting a number of transmission lines. When data arrive on an incoming line a **router** chooses an outgoing line on which to forward them.

More often than not, in a WAN, the hosts and subnet are owned and operated by different organizations and the routers connect different kinds of networking technology. When different networking technologies are connected the WAN is no longer a single network but rather a network of networks, an **internetwork**. In this case the subnet is normally operated by a third party, known as network service provider.

Finally, there are **Virtual Private Networks (VPNs)** enabling the hosts to be connected across shared or public networks as if they were directly connected to the private network, and thus benefit from the functionality, security and management policies of the private network (Mason, 2002).
2.4 Network Software

To reduce the design complexity of computer networks, most of them are organized as stacks of layers. The number of layers, the name, the contents and the function of each layer differ from network to network. The purpose of each layer is to offer certain services to the higher layers while shielding those layers from the details of how the offered services are actually implemented.

When layer \( n \) on one machine carries on a conversation with layer \( n \) on another machine, the rules and conventions used in this conversation are collectively known as the layer \( n \) protocol and the entities comprising the corresponding layers on different machines are called peers. Protocols are the standards that specify how data is represented when being transferred from one machine to another. Protocols specify how the transfer occurs, how errors are detected, and how acknowledgements are passed (Comer, 2000). A three-layer example is illustrated in Figure 2-1.

The data are not directly transferred from layer \( n \) on one machine to layer \( n \) on another machine. Instead, each layer passes data and control information to the layer immediately below it, until the lowest layer is reached. Below layer 1 is the physical medium through which actual communication occurs. In Figure 2-1 virtual communication is shown by dotted lines and physical communication by solid lines.
Between each pair of adjacent layers is an interface. The interface defines which primitive operations and services the lower layer makes available to the upper one. It is crucial that the interfaces between the layers are unequivocally defined. Doing so, in turn, requires that each layer perform a specific collection of well-understood functions. In addition to minimizing the amount of information that must be passed between layers, clear-cut interfaces also make it simpler to replace one layer with a completely different protocol or implementation (e.g., replacing all the telephone lines by satellite channels) because all that is required of the new protocol or implementation is that it offer exactly the same set of services to the upper layer as the old one did.

A set of layers and protocols is called a network architecture. It should be noted that the details of the implementation and the specification of the interfaces is not part of the architecture. It is not necessary that the interfaces on all machines in a network be the same, provided that each machine can correctly use the protocol stack; the list of protocols used by the system, one protocol per layer.

When designing a protocol stack, reliability is a major issue. In essence, reliability is the design issue of making a network that operates correctly even though it is made
up of a collection of components that are themselves unreliable. To improve reliability two main issues have to be addressed.

The first issue is that messages traveling over the network often get corrupted. These errors have to be detected so that the message is resent or, if possible, corrected. In both cases redundant information have to be added.

The second reliability issue is finding a working path through a network. Often there are multiple paths between a source and destination and there may be some broken links or routers. The network should be able to decide automatically which path is the optimal. This topic is called routing.

The second major design issue concerns the evolution of a network. Over time, networks grow larger and new designs emerge that need to be connected to the existing network. As shown earlier in this section, this is generally addressed by dividing the overall problem and hiding implementation details, namely by protocol layering. Since there are many computers on the network, every layer needs a mechanism for identifying the senders and receivers that are involved in a particular message. This mechanism is called addressing or naming, in the low and high layers, respectively. In growing networks, scalability is also an important issue since congestion and other problems might appear, and increasingly complex internetworking solutions have to be employed to address the problem of connecting different technologies, with different limitations.

The third major design issue is the allocation of resources, such as the capacity of transmission lines. Various designs are used, most notably statistical multiplexing, sharing network bandwidth dynamically based on statistics of demand. Another allocation problem is flow control, essentially how to keep a sender from swamping a slower receiver with data. Congestion may also appear when more traffic is being sent than the network can deliver.

Furthermore, resource allocation does not concern just bandwidth. Most networks must provide service to applications that want real-time delivery at the same time that they provide service to applications that want high throughput. Quality of service is the name given to mechanisms that reconcile these competing demands.
The last major design issue is network security. Broadly, this topic’s designs are based on cryptography and include a variety of mechanisms. Mechanisms that provide confidentiality defend against eavesdropping on communications, and they are used in multiple layers. Mechanisms for authentication prevent impersonation in many different settings. Other mechanisms are employed for integrity, preventing surreptitious changes to messages.

Going back to the previous subject of layer interfaces, there are two different types of service that layers can offer to the layers above them: connection-oriented and connectionless. Both of them are manifestations of the two broader approaches to communication networks.

Connection-oriented, sometimes called circuit-switched, networks operate by forming a dedicated connection or circuit between two points (Comer, 2000). Consequently, a connection-oriented network service can be used after a connection has been established. After the connection has been used, it is released. In most connection-oriented network services the bits arrive in the order they were sent. In certain cases, when a connection is established, the sender, receiver, and subnet conduct a negotiation about the parameters to be used, such as maximum message size, quality of service required, and other issues.

On the other hand, connectionless, sometimes called packet-switched, networks take an entirely different approach. Data transferred across a network are divided into data packets, also known as datagrams that are multiplexed onto high capacity inter-machine connections. A data packet, which usually contains only a few hundred bytes, is divided in payload and control information. The latter, found in the packet’s header and trailer, includes among others, the full destination address and identification that enables the network hardware to know how to send it to the specified destination. As a result, a connectionless network service works with packets that are routed through the intermediate nodes inside the system independently and often arrive in an unexpected order (Comer, 2000).

There are many different network services, both connection-oriented and connectionless. None of them is inherently better; they should rather be carefully
chosen according to the needs of each application, in regards to reliability, flexibility and quality of service.

A service is formally specified by a set of primitives available to user processes to access the service. The set of primitives available depends on the nature of the service being provided, so the primitives for a connection-oriented service are different from those of a connectionless service. The primitives of Figure 2-2 can be considered a minimal example.

It should be clear that the service a layer provides to the layer above it, defines what operations the layer is prepared to perform on behalf of its users, not how these operations are implemented. This sharply distinguishes a service from a protocol that is a set of rules governing the format and meaning of the messages that are exchanged by the peer entities within a layer. Entities use protocols to implement their service definitions. They are free to change their protocols at will, provided they do not change the service visible to their users. In this way, the service and the protocol are completely decoupled.

<table>
<thead>
<tr>
<th>Primitive</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>LISTEN</td>
<td>Block waiting for an incoming connection</td>
</tr>
<tr>
<td>CONNECT</td>
<td>Establish a connection with a waiting peer</td>
</tr>
<tr>
<td>ACCEPT</td>
<td>Accept an incoming connection from a peer</td>
</tr>
<tr>
<td>RECEIVE</td>
<td>Block waiting for an incoming message</td>
</tr>
<tr>
<td>SEND</td>
<td>Send a message to the peer</td>
</tr>
<tr>
<td>DISCONNECT</td>
<td>Terminate a connection</td>
</tr>
</tbody>
</table>

*Table 1: Six service primitives that provide a simple connection-oriented service.*

2.5 The TCP/IP Reference Model

After having discussed layered networks in the abstract, we will proceed with arguably the foremost network architecture, the TCP/IP reference model. Although the model itself is of limited use, the protocols are widely used, so understanding it is crucial in order to understand the Digital Internet. It should be noted that there is another very important network architecture, the OSI reference model. This model is very
useful, particularly from an educational standpoint, but the protocols associated with it have fallen in disuse, so it will not be examined here.

The architecture that would later become known as the TCP/IP reference model, after its two primary protocols, was from early on designed with the ability to connect multiple networks in a seamless way as one of its major goals. It was invented as the ARPANET, a research network sponsored by the U.S. Department of Defense, connecting hundreds of universities and government installations using leased telephone lines, had satellite and radio networks gradually added, troubling the existing protocols. This new architecture was first described by Cerf and Kahn (Cerf & Kahn, 1974), and later refined and defined as a standard in the Internet community (Branden, 1989). Other than connecting various technologies, the TCP/IP reference model was highly concerned with flexibility and the ability to survive loss of subnet hardware, without existing conversations being broken off. All these requirements led to the creation of the following four software layers:

\textit{Application Layer}

At the highest layer, users invoke application programs that access services available across a TCP/IP internetwork. An application interacts with one of the transport layer protocols to send or receive data. Each application program chooses the style of transport needed, which can be either a sequence of individual messages or a continuous stream of bytes. The application program passes data in the required form to the transport layer for delivery (Comer, 2000).

\textit{Transport Layer}

The primary duty of the transport layer is to provide communication from one application program to another, often called end-to-end communication. The transport layer may regulate the flow of information. It may also provide reliable transport, ensuring that data arrives without error and in sequence. To do so, transport protocol software arranges to have the receiving side send back acknowledgements and the sending side retransmit lost messages. The transport software divides the stream of data being transmitted into small pieces, often called segments, and passes each segment along with a destination address to the next layer for transmission.
Since a general purpose computer can have multiple application programs accessing an internetwork at one time, the transport layer must accept data from several user programs and send it to the next lower layer. To do so, it adds additional information to each segment, including codes that identify which application program sent it and which application program should receive it, as well as a checksum. The receiving machine uses the checksum to verify that the message arrived intact, and uses the destination code to identify the application program to which it should be delivered (Branden, 1989; Comer, 2000).

**Internet Layer**

As the Internet layer handles communication from one machine to another, it accepts a request to send a segment from the transport layer along with an identification of the machine to which the segment should be sent. It encapsulates the segment in packets, filling in an IP header, uses a routing algorithm to determine whether to deliver each packet directly or send it to a router, and passes the packet to the appropriate network interface for transmission.

The Internet layer also handles incoming packets, checking their validity, and uses the routing algorithm to decide whether the packet should be processed locally or forwarded. For packets addressed to the local machine, software in the internet layer deletes the IP header, and chooses from among several transport protocols the one that will handle the segment. Finally, the Internet layer sends and receives ICMP error and control messages as needed (Branden, 1989; Comer, 2000).

**Link Layer**

The lowest layer TCP/IP software is responsible for accepting packets and transmitting them over a specific network. This means that it largely functions as a network interface. The link layer may consist of a device driver or a complex subsystem that uses its own data link protocol (Branden, 1989; Comer, 2000).

A fifth layer is often added to illustrate the hardware on which the software layers are based (Comer, 2000). Furthermore, there are various protocols corresponding with each of the four software layers. Although, we will not discuss specific protocols here, some of the most widely used ones are listed below: Application Layer: Domain Name
Network protocols for the Physical Internet


2.6 Architecture of the Digital Internet

In this section, we will attempt to give a brief overview of the current architecture of the most successful internetwork, the Digital Internet, but it should be noted that this architecture is continuously changing. In certain cases, this means it is hard to define even fundamental aspects of the Digital Internet. Consequently, the description given here will be of necessity somewhat simpler than reality and what is true now may not be true in the near future.

A simplified, and rather conservative, overview is shown in Figure 2-3. Let us examine this figure piece by piece, starting with a computer at home (at the edges of the figure). To join the Digital Internet, the computer is connected to an Internet Service Provider (ISP), from who the user purchases access or connectivity. This allows the computer to exchange messages with all of the other accessible hosts on the Digital Internet. There are many kinds of Digital Internet access, and they are usually distinguished by the bandwidth they provide and their cost, but the most important attribute is connectivity.
Several ways to connect to an ISP are shown in Figure 2-3. Two of them will be examined here. The first way to connect to an ISP is by using a phone line, in which case the phone company is also an ISP. Digital Subscriber Line (DSL), reuses the telephone line that connects to a house for digital data transmission. The computer is connected to a device called a DSL modem, short for “modulator demodulator”, that converts between digital packets and analog signals that can pass unhindered over the telephone line. At the other end, a device called a Digital Subscriber Line Access Multiplexer (DSLAM) converts between signals and packets.

The access DSL provides is limited by the bandwidth of the “last mile” of transmission. By running optical fiber to residences, faster Digital Internet access can be provided at rates on the order of 10 to 100 Mbps. This design is called Fiber to the Home (FTTH). For businesses in commercial areas, it may be advisable to lease a high-speed transmission line from the offices to the nearest ISP.

When the connection between the customer and the ISP has been established, customer packets enter the ISP network for service at a location called the ISP’s Point of Presence (POP). From this point on, the system is fully digital and packet switched as packets are moved between the POPs of different ISPs.

ISP networks may be regional, national, or international in scope. Their architecture is made up of long-distance transmission lines that interconnect routers at POPs in the
different cities that the ISPs serve. This equipment is called the backbone of the ISP. If a packet is destined for a host served directly by the ISP, that packet is routed over the backbone and delivered to the host. Otherwise, it must be handed over to another ISP.

ISPs connect (peer) their networks to exchange traffic at Internet eXchange Points (IXPs) around the world. They are drawn vertically in Figure 2-3 because ISP networks overlap geographically. Basically, an IXP is a room full of routers, at least one per ISP. A LAN in the room connects all the routers, so packets can be forwarded from any ISP backbone to any other ISP backbone. IXPs can be large and independently owned facilities.

The peering that happens at IXPs depends on the business relationships between ISPs. For example, a small ISP might pay a larger ISP for connectivity to reach distant hosts, much as a customer purchases service from an ISP. In this case, the small ISP is said to pay for transit. Alternatively, two large ISPs might decide to exchange traffic so that each ISP can deliver some traffic to the other ISP without having to pay for transit. That often leads to a situation where ISPs publicly compete with one another for customers but privately cooperate to do peering (Metz, 2001).

The path a packet takes through the Digital Internet depends on the peering choices of the ISPs. If the ISP delivering a packet peers with the destination ISP, it might deliver the packet directly to its peer. Otherwise, it might route the packet to the nearest place at which it connects to a paid transit provider so that provider can deliver the packet. Two example paths across ISPs are drawn in Fig. 1-29. Often, the path a packet takes will not be the shortest path through the Internet.

The ISP market is dominated by very few companies that operate large international backbone networks with thousands of routers connected by high-bandwidth fiber optic links. These ISPs do not pay for transit. They are usually called tier 1 ISPs and are said to form the backbone of the Digital Internet, since everyone else must connect to them to be able to reach the entire internetwork.

Companies that provide much content, like Google, locate their computers in data centers that are well connected to the rest of the Digital Internet. These data centers are designed for computers, not humans, and may be filled with hundreds of thousands of machines of machines called a server farm. Colocation or hosting data centers let
customers put equipment such as servers at ISP POPs so that short, fast connections can be made between the servers and the ISP backbones. The Digital Internet hosting industry has become increasingly virtualized so that it is now common to rent a virtual machine that is run on a server farm instead of installing a physical computer. As explained earlier, this is known as cloud computing and allows much more cost-effective resource utilization (Vaquero, et al., 2009). These data centers are so large that electricity is a major cost, so data centers are sometimes built in areas where electricity is cheap or alternatives, like water cooling, are easily accessible (Schulz, 2009).

This ends the overview of the Digital Internet. As mentioned earlier, certain protocols and other aspects of the Digital Internet that were only mentioned in passing will be further examined when needed, in following chapters.
Chapter 3. Logistics Networks and the Physical Internet

In this chapter we will explore the concept of the Physical Internet. In the beginning of the chapter, the unsustainability of contemporary logistics is asserted. The Physical Internet is subsequently defined and proposed as a solution to this unsustainability. Then, the current status of research and experimentation on the Physical Internet will be discussed, showcased by active and past projects, alongside some early insights regarding the key issues and prospects of its implementation.

3.1 The Unsustainability of Contemporary Logistics

The way physical objects are currently transported, handled, stored, realized, supplied and used throughout the world is not sustainable. This unsustainability assertion, supported through numerous symptoms, is outlined in this section. Addressing this global unsustainability is a worldwide grand challenge, hereafter termed the Global Logistics Sustainability grand challenge (Montreuil, 2011).

From an economic perspective, the way goods are flowed is very costly, accounting for a significant part of the Gross Domestic Product (GDP) of most countries throughout the world. The scale of the global logistics market is estimated to reach $8 trillion in 2020 (Park & Lee, 2015). This is affecting the everyday life of consumers. On average, logistics costs account for 10-15% of the final cost of the finished product (Commission of the European Communities, 2006). In the developing world, various forms of inefficiency mean the figure is more often in the range of 15-25% (Ojala, et al., 2008).

From an environmental perspective, freight transport is problematic, being one of the largest sources of greenhouse gas emissions. A typical example is France, where freight transport generated 14% of the country’s greenhouse gas emissions as of 2006, having grown by an annual rate of +23% since 1990 (Duong & Savy, 2008), while the objective of the European Union (EU) for 2020 is an overall reduction of greenhouse gas emissions by 20% compared to 1990 levels (Commission of the European Communities, 2008). At the same time, road transport has been increasing its share of the total freight transport (Duong & Savy, 2008). This is particularly alarming as road
transport still consumes significantly more energy per tkm than rail or ship freight transport, in spite of energy efficiency improvements of both light and heavy duty trucks during the last decades throughout Europe (European Environment Agency, 2015).

From a societal perspective, contemporary logistics cause hardship, particularly to those working within the sector, the most extreme example being the truck drivers (de Croon, et al., 2004). The rest of society is also affected, primarily by the high economic and environmental costs of logistics, translated for example in higher commodity prices, while the level of service, reliability and functionality is often deemed unsatisfactory (Montreuil, 2011; Commission of the European Communities, 2006).

As it is evident from the three last paragraphs, the unsustainability of contemporary logistics manifests itself along three basic axes; an economic, an environmental and a societal. Consequently, the goals of the Global Logistics Sustainability grand challenge can be built along these three axes.

Along the economic axis, the goal is to unlock highly significant gains in global logistics, production, transport and business productivity. Along the environmental axis, the goal is to reduce by an order of magnitude the global energy consumption, direct and indirect pollution, including greenhouse gas emission, associated with logistics, production and transport. Along the societal axis, the goal is to significantly increase the quality of life of the logistic and production workers, as well as of the overall population by making the objects and functionality that consumers need and value much more accessible across the world (Montreuil, 2011).

The overall goal of the grand challenge can be summarized as a quest to enable the economic, environmental and societal sustainability of physical object mobility (transport, handling), storage, realization (production, assembly, finishing, refurbishing and recycling), supply and usage (Montreuil, 2011).

Before proceeding to the proposed solution to the grand challenge, a few selected unsustainability symptoms will be reported, showcasing the asserted unsustainability of contemporary logistics.
1. Excessive empty and near-empty travel

Vehicles and containers may not always be full at departure, and a large portion of the non-empty space is often being filled by packaging. Furthermore, vehicles leaving loaded get progressively emptier as their route unfolds from delivery point to the various points of delivery. Then, they often return empty or incur extra travel routes to find return shipments. These practices are surprisingly common. In the EU, 25% of trips are empty and non-empty trucks use, on average, 56% of their weight capacity (Eurostat, 2007).

2. Truck drivers suffer

Truck drivers are arguably the most harshly affected part of society. They tend to experience psychological strain as result of their work, leading to high voluntary turnover. In fact, the average tenure for a truck driver is just 9–12 months. Also, job movement to any job outside the trucking industry tends to result in a larger strain reduction as compared to job movement within the trucking industry, further proving that the work as a truck driver puts a heavy strain on the driver’s psychological wellbeing (de Croon, et al., 2004; Williams, et al., 2011).

3. Suboptimal storage and distribution of products

Manufacturers, distributors, retailers and users are storing products, often in vast quantities, through their networks of warehouses and distribution centers, yet service levels and response times to local users are often constraining and unreliable. Furthermore, a significant portion of the finished consumer goods do not reach the right market on time, ending up unsold, while they would have been required elsewhere. Unfortunately, hard statistics on this sensitive issue are rare, yet it is believed to be common, particularly in the food and clothing industries (Montreuil, 2011).

4. Suboptimal usage and location of production and storage facilities

Many businesses invest in storage and/or production facilities which are lowly used for significant parts of the year, or yet badly used, dealing with products which would have better been dealt with elsewhere, forcing a lot of unnecessary travel. For example,
warehouses are often under-utilized for large portions of the year due to the seasonal nature of some products, while these same facilities are over-taxed during their peak, leading to inefficient, short-term practices to meet peak demand. The volume of unnecessary travel could have been diminished by more efficient routing and/or production near the products’ final destination. The outsourcing of product manufacturing to developing countries has accentuated this phenomenon. Yet, even without outsourcing, factors such as the hub-and-spoke networks and the centralization phenomenon would still case excessive travel (Montreuil, 2011).

5. Insufficient support for intermodal synchronization

Although the benefits of intermodal transport have been proven by many successful projects, notably associated with containerized cargo (Crainic & Kim, 2007), and both technological and business models are available (Fjortoft, et al., 2011; Nikitakos & Lambrou, 2007), widespread implementation is still facing challenges. The changes in procedures and the increasing reliance on IT are often viewed with suspicion by Unions, despite their essential role for intermodal transport systems (Vanelslander, et al., 2013). At the same time, the European authorities and certain industries, such as the coastal shipping industry, show only reluctant support. As a result, in addition to suboptimal efficiency and effectiveness, the inadequate support for intermodal transport denies a significant competitive advantage to energy efficient alternatives; unintentionally favoring energy intensive road transport solutions (Kapros & Panou, 2007).

6. Cities unsuitable for logistics

Most cities are not designed and equipped appropriately for freight transport, handling and storage. Consequently, the feeding of businesses and users inside urban areas is hindered, while the citizens suffer significant traffic congestion, noise and pollution (Montreuil, 2011). This in turn has profound effects on the economy. Congestion, mostly located in and around urban areas, costs nearly 1 % of the EU’s GDP, annually (European Commission, 2011).
7. Fragile logistics networks

There is a very high concentration of operations in a limited number of centralized production and distribution facilities, with travel along a narrow set of high traffic routes. This compromises both the security of logistics networks and supply chains of many businesses in the face of deliberate attacks and their robustness in face of accidents, natural disasters and demand crises (Joint Transport Research Centre, 2009; Peck, 2007). The problem is even greater in developing countries where transport and logistics infrastructures, capabilities and services are inadequate (Montreuil, 2011).

8. Innovation and automation are discouraged

There is little coordination and uniformity on the design of unit loads, with the notable exception of shipping containers (Levinson, 2006), so the operators of vehicles, handling systems and facilities are often discouraged from introducing connective technologies, systemic handling and transport automation and wider collaboration. The lack of coordination and uniformity is also manifested by the absence of general standards and protocols. This is discouraging breakthrough innovation, allowing only for marginal improvements (Montreuil, 2011).

Figure 3-1 relates the selected eight symptoms to the economic, environmental and societal axes of the unsustainability of contemporary logistics. All symptoms combine significant negative economic impact with a negative environmental and/or societal impact. The eight symptoms are meant provide glimpses of the unsustainability of contemporary logistics; they do not provide an exhaustive list of the problems and the manifestations of unsustainability in the fields of logistics.
Unsustainability Symptoms

<table>
<thead>
<tr>
<th>Unsustainability Symptoms</th>
<th>Economic</th>
<th>Environmental</th>
<th>Societal</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Excessive empty and near-empty travel</td>
<td>●</td>
<td>●</td>
<td></td>
</tr>
<tr>
<td>2. Truck drivers suffer</td>
<td>●</td>
<td>●</td>
<td></td>
</tr>
<tr>
<td>3. Suboptimal storage and distribution of products</td>
<td>●</td>
<td>●</td>
<td></td>
</tr>
<tr>
<td>4. Suboptimal usage and location of production and storage facilities</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>5. Insufficient support for intermodal synchronization</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>6. Cities unsuitable for logistics</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>7. Fragile logistics networks</td>
<td>●</td>
<td>●</td>
<td></td>
</tr>
<tr>
<td>8. Innovation and automation are discouraged</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
</tbody>
</table>

Table 2: Selected unsustainability symptoms of contemporary logistic.

3.2 The Physical Internet Vision

The Global Logistics Sustainability grand challenge, with its three-pronged goal, cannot be effectively addressed within the very framework that has created the problem. The current paradigm must be replaced by a new one, designed and implemented through a meta-systemic approach.

The Physical Internet has been proposed as a solution to this challenge. It is a new paradigm that has the potential of addressing the Global Logistics Sustainability challenge by revolutionizing the fields of material handling, logistics and facilities design (Lounès & Montreuil, 2011).

The Physical Internet is defined as an open global logistics system founded on physical, digital and operational interconnectivity through encapsulation, interfaces and protocols. It is meant to be a perpetually evolving system driven by technological, infrastructural and business innovation (Montreuil, et al., 2012).

Montreuil (2011) has introduced a set of thirteen characteristic that outline the new paradigm:
1. Encapsulation of merchandizes in world-standard smart green modular containers

Some of the most efficient logistics systems are associated with standardization; on the large side, with the transport, handling and storage of the world-standard 1 or 2 TEU shipping containers (Levinson, 2006), and on the small side, with parcel logistics as deployed by companies such as DHL, FedEx and UPS. The Physical Internet generalizes and significantly extends this praxis.

The Physical Internet encapsulates physical objects in packets or containers, hereafter termed \( \pi \)-containers, so as to differentiate them from current containers. These \( \pi \)-containers are world-standard, smart, green and modular containers. They are notably modularized and standardized worldwide in terms of dimensions, functions, and fixtures. The key functional specifications of \( \pi \)-containers are (Montreuil, et al., 2010):

- Unitizing merchandise as their content so that it is not dealt with explicitly by the Physical Internet;
- Coming in various modular sizes, from the cargo container sizes down to tiny sizes;
- Easy to flow through various transport, handling, and storage modes and means;
- Easy to handle, store, transport, seal, clench, interlock, load, unload, construct, dismantle, panel, compose, and decompose;
- Smart tag enabled, with sensors if necessary, to allow their proper identification, routing, and maintaining;
- Made of environment friendly materials, with minimal off-service footprint;
- Minimizing packaging materials requirements through the enabling of fixture-based protection and stabilization of their embedded products;
- Coming in various usage-adapted structural grades;
- Having conditioning capabilities (e.g., temperature) as necessary;
- Sealable for security purposes.

Neither the current containers nor parcels respect all these functional specifications, so \( \pi \)-containers have to be designed. Figure 3-2, depicts the needed modularity of \( \pi \)-containers by illustrating how composite \( \pi \)-containers can be composed from unitary \( \pi \)-containers and later decomposed into sets of unitary and smaller composite \( \pi \)-
containers. The π-containers are key elements enabling the interoperability necessary for the adequate functioning of the Physical Internet.

Figure 3: The modularity of unitary and composite π-containers (Montreuil, 2011).

2. Aiming towards universal interconnectivity

A fundamental aim when conceptualizing and implementing the Physical Internet is universal interconnectivity. This transposes in a quest for high-performance logistics centers, systems and movers exploiting world-standard protocols making it fast, cheap, easy, and reliable to interconnect π-containers through modes and routes.

The nodes of the Physical Internet are concurrently routing and accumulation sites and facilities within the networks, as well as gateways interfacing with the entities out of the Physical Internet.

As currently conceived, the activities of sorting, storage, and handling physical objects are most often brakes to interconnection. This occurs in train sorting yards as well as in cross-docking platforms. However, there exist exceptions, such as some of the recently implemented and reengineered container ports.

The Physical Internet generalizes and functionally standardizes unloading, orientation, storage, and loading operations, widely applying them to π-containers in a smart automated and/or human-assisted way. This universal interconnectivity between
automatic, automated, mechanically assisted, and manual operations is of upmost necessity. In parallel, the minimization of the temporary and economic requirements of load breaking is an essential objective of the universal interconnectivity through the Physical Internet.

3. Evolve from material to $\pi$-container handling and storage systems

In the Physical Internet, there are no generic material handling and storage systems. There are only $\pi$-container material handling and storage systems embedding innovative technologies and processes exploiting the characteristics of $\pi$-containers to enable their fast, cheap, easy and reliable input, storage, composing, decomposing, monitoring, protection and output through smart, sustainable and seamless automation and human handling (Montreuil, et al., 2010).

The $\pi$-container handling and storage systems have the following functional capabilities:

- Enabling fast and reliable input and output performance;
- Seamless interfacing with vehicles and systems moving products in and out, as well as with client software systems for tracking and interfacing with the $\pi$-container;
- Monitoring and protecting the integrity of $\pi$-container;
- Securing the $\pi$-container to the desired level;
- Providing an open live documentation of their specified performance and capabilities and of their demonstrated performance and capabilities, updated through ongoing.

As introduced in (Montreuil, et al., 2010), the $\pi$-nodes of the Physical Internet are composed of sites, facilities, and systems such as:

- $\pi$-transit: transferring $\pi$-carriers (carrying $\pi$-containers) from their inbound $\pi$-vehicles to their outbound $\pi$-vehicles;
- $\pi$-switch: Transferring uni-modally $\pi$-containers from an incoming $\pi$-mover to a departing $\pi$-mover;
• π-bridge: transferring multi-modally π-containers on a one-to-one basis not involving any multiplexing;
• π-sorter: receiving π-containers from one or multiple entry points and sorting them so as to ship each of them from a specified exit point, potentially in a specified order;
• π-composer: constructing composite π-containers from specified sets of smaller π-containers, usually according to a specified 3D layout, and/or dismantling composite π-containers into a number of π-containers that may be either smaller unitary or composite π-containers;
• π-store: storing π-containers during agreed upon target time windows;
• π-gateway: receiving π-containers and releasing them so they and their content can be accessed in a private network not part of the Physical Internet, or receiving π-containers from a private network out of the Physical Internet and registering them into the Physical Internet, directing them toward their first destination along their route across the Physical Internet;
• π-hub: transfer π-containers from incoming π-movers to outgoing π-movers.

Each of the above is strictly dedicated to π-containers and designed to perform smoothly and effectively in the Physical Internet. Thus, as detailed in (Montreuil, et al., 2010), they are in general more streamlined and standardized than their current counterparts.

4. Exploit smart networked containers embedding smart objects

The Physical Internet exploits the capabilities of the smart π-containers’ connectivity, for improving the performance perceived by the clients and the overall performance of the Physical Internet.

Each smart π-container has a unique worldwide identifier and a smart tag to act as its representing agent. The smart tag helps insuring the identification, integrity, routing, conditioning, monitoring, traceability, and security of each π-container. It also enables the distributed handling, storage, and routing automation (Montreuil, et al., 2010). The smart tag exploits technologies such as RFID or GPS (Finkenzeller, 2010; Johnson, 2008) as well as other elements of the Internet of Things (IoT) (ITU, 2005). More
broadly, the Physical Internet is to exploit as best as possible the IoT to enable the ubiquitous connectivity of its \( \pi \)-containers and \( \pi \)-systems.

5. Evolve from point-to-point hub-and-spoke transport to distributed multi-segment intermodal transport

Current logistics are dominated by a combination of point-to-point transport and hub-and-spoke transport. Even though these two ways are feasible in the Physical Internet, the dominance shifts to distributed multi-segment intermodal transport.

Currently, long distance road transport is usually done by one driver and one truck assigned to the multi-day trip. The driver will drive all the way to destination, probably sleeping in the truck. Once having made the delivery, the driver will either return to the original point of departure with an empty track, or move the truck to some as nearby as possible location to pick up a new delivery returning towards a location as near as possible to the original point of departure, in order to avoid empty travel.

In the Physical Internet, such a point-to-point experience would be exceptional. Most probably, a first driver-truck duo would be assigned to transport the delivery to a transit a few hours away. The delivery would then be deposited to a slot in a \( \pi \)-transit or \( \pi \)-hub. The first duo would then pick up another delivery returning to the point of departure. A second driver-truck duo would soon afterward pick up the delivery and move it another segment forward, or yet the containers could be transferred to other trailers, trucks, trains, ships, or planes as pertinent given the opportunities. The process would be repeated until all the containers of the delivery have reached the final destination. The shippers or their representatives would have a priori arranged transport on each segment and sojourn at each \( \pi \)-transit or \( \pi \)-hub, in their best interests in terms of price, timing and risk; or yet the routing decisions would be dynamic and/or distributed, made as opportunities unfold through the trip.

In general, the shift is toward distributed multi-segment travel of \( \pi \)-containers through the Physical Internet with:

- Distinct carriers and/or modes taking charge of internode segments;
- Hubs and transit nodes enabling synchronized transfer of \( \pi \)-containers and/or carriers between segments;
• Web software platform enabling an open market of transport requesters and transport providers.

Distributed multi-segment travel can be achieved with various degrees of decision-making centralization and autonomy. Ultimately, shippers would just state to their \( \pi \)-containers when and where they have to go or stand, what kind of budget is allowed, and they would depart with no further intervention from the shippers. Their smart and connected nature, coupled with the smartness and connectivity of the various Physical Internet elements, would enable decisions to be taken on the spot, given new current information on opportunities and constraints. The \( \pi \)-containers would decide on their routing dynamically, adapting their plans in route. They would call back to the shippers or their representatives human or virtual logistic agents only in cases of out-of-bound situations where special circumstances make it forecast an improbable arrival on time and on budget, or when their physical or informational integrity and security are in danger.

Another option leaves minimal decision-making to the \( \pi \)-container, which simply relays information to agents that take the decisions in its place, and transmit them to both the \( \pi \)-container and, when appropriate, the Physical Internet elements involved in the route. The agents either take the routing decisions on a one-by-one basis or considers a number of \( \pi \)-containers under their control. The \( \pi \)-containers and local \( \pi \)-elements only take initiative in cases of the agents’ unavailability or incapability to respond in time to urgent decisional need.

In another option nearer to current norms, the shippers or their logistic agents are securing complete routes prior to departure. As an alternative way, they may impose a set of key intermediary nodes and/or links, leaving the rest to more autonomous decision-making. All these options rely on the logistic providers exploiting the nodes, links and movers to rapidly and reliably provide users, their agents or their \( \pi \)-containers as pertinent, with their availabilities, capabilities, performance histories and pricings through the Digital Internet, and the capability to secure transactions digitally.

There is a significant difference between having to ship once a set of \( \pi \)-containers once and having to do so repeatedly. It is entirely possible for the shipper to leverage his long-term recurrent need with various providers to secure an economically viable solution, mixing some long-term contracts and some dynamic on-the-fly decision areas.
6. Embrace a unified multi-tier conceptual framework

The Physical Internet is to be based on the same conceptual framework whatever the scale of the involved networks. Networks will be embedded in wider networks, each operating according to Physical Internet protocols and standards:

1. Intra-center inter-processor networks;
2. Intra-facility inter-center networks;
3. Intra-city inter-facility networks;
4. Intra-state inter-city networks;
5. Intra-country inter-state networks;
6. Intra-continental inter-country networks;

As an example, at the fourth level, the Physical Internet is to structure inter-city travel with \( \pi \)-transits and \( \pi \)-hubs strategically deployed by a variety of providers at key locations such as country borders, proximity to ports and airports, proximity to intersections of highways and other key roads, and city surroundings.

7. Activate and exploit an Open Global Supply Web

Given the current logistics organization, producers, distributors, and retailers rely mostly on private supply chains and supply networks, constituted of the production and distribution centers of the their enterprise and those of their partners. Some rely on third-party logistics providers, yet they are mostly bound to sign long-term contracts with the providers who mostly dedicate facilities to them.

The Physical Internet enables to shift from private supply networks to an Open Global Supply Web enabling the physical equivalents of Intranets, Virtual Private Networks, Cloud Computing and Cloud Storage.

Supply webs are networks of interrelated supply networks, each embedding interlaced supply chains, involving multiple organizations with collaborative or
competitive relationships (Hakimi, et al., 2009; Montreuil, et al., 2009). Open supply webs are supply webs with the following characteristics:

1. Their nodes are openly accessible to most actors, be they producers, distributors, logistics providers, retailers, or users;
2. The service capacity of their nodes is available for contract on demand, on a per-use basis, be it for processing, storage or moving activities;
3. Dynamic and interlaced virtual private networks are created by actors for realizing and deploying the products, services and solutions in anticipation of and response to stochastic demand from clients.

In the current logistics organization, most warehouses and distribution centers are used by few distinct enterprises, with the vast majority by a single enterprise. Also, most enterprises operate one or just a few warehouses or distribution centers, rarely going beyond twenty.

In the Physical Internet, the fact that products and materials are moved and stored on standard, modular, smart and secured \(\pi\)-containers allows warehouses and distribution centers to accept handling and storing \(\pi\)-containers from a wide variety of clients, embedding an indeterminate and non-pertinent number of distinct products, as long as they respect their throughput, security, conditioning and dimensioning capability specifications.

Overall, the Physical Internet enables a Global Open Supply Web. It is characterized by a worldwide open web of product realization centers, distribution centers, warehouses, hubs and transit centers enabling producers, distributors and retailers to dynamically deploy their \(\pi\)-container-embedded products in multiple geographically dispersed centers, producing, moving and storing them for fast, efficient and reliable response delivery to distributed stochastic demand for their products, services, and/or solutions. This has significant potential positive consequences for enterprises, notably in terms of supply productivity, responsiveness, adaptability, and resilience.
8. Design products fitting containers with minimal space waste

The Physical Internet embeds physical objects (freight, merchandises, products, materials) within modular $\pi$-containers. Thus, the objects to be carried within $\pi$-containers have to be designed and engineered so as to minimize the load they generate on the Physical Internet, with dimensions adapted to standard container dimensions. Indeed, the aim is for them to have maximal volumetric and functional density while containerized, fitting within the $\pi$-containers modular dimensions and extendable to their usage dimensions when necessary.

Functional density of an object is here defined as the ratio of its useful functionality over the product of its weight and volume.

A goal is for each physical object to be dealt with by the Physical Internet to fit in a $\pi$-container as small as possible so as to avoid moving and storing air within the $\pi$-containers. Another goal is for physical objects to be designed so that only their key components and modules have to travel extensively through the Physical Internet, and that they be easy to finish near point of use by exploiting locally available objects.

9. Minimize physical moves and storages by digitally transmitting knowledge and materializing objects as locally as possible

In general, it is easier, faster and more economical, to move and to store digital objects composed of information bits rather than physical objects composed of matter. This favors the extensive exploitation of knowledge-based dematerialization of products and their materialization as physical objects at point of use when necessary.

In order to enable such behavior, the Physical Internet is to be connected to ever more open distributed flexible production centers capable of locally realizing (making, assembling, finishing, personalizing) for clients a wide variety of products from combinations of digitally transmitted specifications, local physical objects and, if necessary, critical physical objects brought in from faraway sources. Such open production centers are to further enrich and empower the global open supply web.

Third-party production is to take an ever-growing share of the overall production market, with internal production ever more limited to highly sensitive core physical
objects. This notably requires that product realization knowledge should be protected and that authenticity of the materialized products should be legally acknowledged.

It should also be noted that the synergy between this ninth characteristic of the Physical Internet and the seventh one, is expected to hugely increase the performance gains along the way from independent private networks to open supply webs exploiting both open distribution and realization centers.

10. Deploy open performance monitoring and capability certifications

The Physical Internet relies on live open monitoring of the actual performance of all Physical Internet actors and entities, focusing on key performance indices of critical facets such as speed, service level, reliability, safety, and security.

Live performance tracking is openly available, to enable fact-based decision-making and stimulate continuous improvement. The open information is provided while respecting confidentiality of specific transactions. The set of specific performance monitoring to be posted by various types of π-entities has to be the subject of world standards.

Furthermore, the Physical Internet is to do so with its multitude of actors and elements. It is to rely on multi-level Physical Internet capability certification of its containers, handling systems, vehicles, information systems, ports, hubs, distribution, roads, protocols, processes, and so on.

A π-certified container would meet all functional specifications for such containers (Montreuil, et al., 2010), notably respecting the standard dimensions. The multi-level certification could discriminate specific facets of the container. As examples, there could be several security certification levels and several smartness levels. Their structural strength would also be certified.

A π-certified conveyor would be proven to have the capability to convey π-containers within specified dimensions and weights. Multiple levels could discriminate its performance monitoring and π-container tracking capabilities as well as its autonomous routing smartness.

A π-road could be certified to have the capability of monitoring digitally and visually the π-vehicles, π-carriers and π-containers circulating on it, of securing their
passage through it, and of guaranteeing a throughput time with a comprehensive level of systemic reliability.

At higher scales, cities and regions could be \( \pi \)-certified, subject to strict capability measures insuring that, within their boundaries, freight is dealt by \( \pi \)-elements according to Physical Internet protocols.

The combination of open live performance monitoring and capability certifications enables users to plan shipments and sojourns through the Physical Internet. It allows the various actors and elements to rely on each other based on fact-based evidence. It also promotes excellence as actors will benchmark themselves according to posted performance records and capabilities; so they will have an incentive to improve their certification levels.

11. Prioritize webbed reliability and resilience of networks

The overall Physical Internet, as a network of networks, should warrant its own reliability and that of its containers and shipments through its intrinsic nature, its protocols and its structure. The webbing of the networks and the multiplication of nodes should allow the Physical Internet to insure its own robustness and resilience to unforeseen events (Peck, 2007).

Overall, the Physical Internet’s actors, movers, routes, nodes and flowing containers should interact in synergy to guarantee:

- The integrity of physical objects encapsulated in \( \pi \)-containers;
- The physical and informational integrity of \( \pi \)-containers, \( \pi \)-movers, \( \pi \)-routes and \( \pi \)-nodes;
- The informational integrity of \( \pi \)-actors such as humans and software agents;
- The robustness of client-focused performance in delivering and storing \( \pi \)-containers.

12. Stimulate business model innovation

Essential in the Physical Internet vision is a worldwide set of actors with innovative business models (Osterwalder & Pigneur, 2010) commercializing novel offers enabled
by and adapted to the Physical Internet, with innovative revenue models for the various stakeholders.

The advent of the Physical Internet has the potential to simulate the creation of new businesses and innovative business models. This business model innovation is expected to occur in various logistics and transport industries, as well as, in the retailing, service, distribution and manufacturing industries. Both private and public organizations, authorities and research institutes, will innovate in order to provide solutions for the new strengths and weaknesses they will experience and the threats and opportunities they will face in the new paradigm.

13. Enable open infrastructural innovation

The systemic coherence and universal interconnectivity of the Physical Internet are to facilitate the transparent usage of handling, storage, and transport means, enabling their full potential to achieve a positive environmental impact.

The Physical Internet homogeneity in terms of modular $\pi$-containers encapsulating physical objects is to allow a much better utilization of means and modes, thus increasing the capacity of infrastructures by the exploitation of standardizations, rationalizations, and automations through currently unreachable innovations. In general, the Physical Internet eases the technical design and engineering of the entire logistics infrastructure, including the vehicles and carriers, the hubs and the connections with the logistics networks. Consequently, economically, environmentally and socially efficient infrastructure could become not just feasible but also attractive.
Table 3: The unsustainability symptoms addressed by the Physical Internet.

Figure 3-3 provides a matrix mapping of the key Physical Internet characteristics, as described by Montreuil (2011), and some of the unsustainability symptoms, as described in section 3.1, they are meant to address. This mapping is subject to judgment since there are interlacing synergies among the Physical Internet characteristics so they may also impact indirectly other symptoms.
3.3 Towards a Physical Internet

As evident from the last two sections, the Physical Internet could revolutionize the way physical objects are transported, handled, stored, supplied, realized, and used across the world. It is a complex vision of both huge scale and huge scope. Yet, its requirements are not outside the reach of modern science and technology (Montreuil, 2011); in fact there are already numerous projects and research studies trying to realize many aspects of the Physical Internet (ETP ALICE, 2014).

The main objective of this section is to provide an overview of these projects and research studies. Yet, it should be understood that such initiatives, despite being necessary, are not sufficient. There is a need for a macroscopic, holistic, systemic vision offering a unifying, challenging and stimulating framework. This is the role intended for the Physical Internet vision (Montreuil, 2011).

To bring about the Physical Internet, an open and interconnected network of compatible hubs is needed as a foundation. \( \pi \)-containers moving over this network belong to many different parties, enabling full horizontal and vertical collaboration; but the secure handling of both information and \( \pi \)-containers is becoming increasingly challenging. Shipments are optimized for the whole network, requiring a constant quest for the optimal capacity use of transport and warehousing. In order to reach the necessary interoperability of the network, a modular logistic units system has to be designed (ETP ALICE, 2014; Montreuil, 2011).

All these cannot happen in a single gigantic leap forward. The progression toward making the vision a reality has rather to operate according to an ongoing logic of cohabitation and progressive development and deployment that will take decades. On the one hand, research will be constantly expanding the frontiers of the Physical Internet. On the other hand, the implementation will be propelled by actors integrating gradually its aspects and finding ever more value in its usage and exploitation. The combination of the two will guarantee a smooth gradual transition to the new reality of the Physical Internet (ETP ALICE, 2014; Montreuil, 2011).

In that light, some of the initiatives and projects related to the goals of the Physical Internet are presented in this section, in an attempt to provide a mapping of the current status of research, experimentation and early implementation of the Physical Internet:
The International Physical Internet Initiative

The International Physical Internet Initiative (www.physicalinternetinitiative.org) is the earliest research initiative in the field. The team includes Benoit Montreuil (2011), the researcher that first introduced the very concept of the Physical Internet, and a number of researchers and students, notably Eric Ballot and Russell D. Meller (Ballot, et al., 2010; Montreuil, et al., 2010).

Researchers affiliated with the initiative participated in most of the early research about conceptualization and realization of the Physical Internet (Montreuil, 2011; Montreuil, et al., 2010). The initiative boasts a book (Ballot, et al., 2015) and a number of publications that have often been released in accordance to projects that have also been conducted within the initiative, providing overwhelmingly positive results about the potential of the proposed new paradigm.

One of these projects was OpenFret (Ballot, et al., 2010), that provided early insights in the design of road-rail hubs in accordance to the principles of the Physical Internet, funded by PREDIT.

In 2011, another PREDIT Project, Simulation of the Physical Internet Contribution in Solving Logistics Problems: Application on Retail Industry in France, was launched, aiming to demonstrate through simulation the relevance of the Physical Internet concept using data from French supermarkets (Hakimi, et al., 2010).

OTC-KAYPAL® MR (Open Tracing Container), was also launched in 2011. The project demonstrated the use of RFID and Electronic Product Code Information Services (EPCIS) standards and technologies, associated with the Physical Internet concept, coupled to Discovery Services and Business Web Services adapted and applied to an innovative and collaborative business model. Doing so significantly improved the efficiency, visibility, transparency, guidance and traceability of reusable container flux and of their content, evolving in an open loop in the wide distribution universe (Pan & Ballot, 2014).

Another project, was the CELDi Physical Internet Project (Meller, et al., 2012). The project examined quantitatively the extent of the potential benefits, notably in terms of profits, environmental sustainability and reliability, that the swift from current...
horizontal collaborative logistics to the Physical Internet can provide. The project also provides some early insights on the challenges the new paradigm may face, as well as on the possible paths for its successful implementation.

The biggest project the International Physical Internet Initiative contributed to was MODULUSHCA (Modular Logistics Units in SHared co-Modal networks). The consortium was coordinated by PTV Planung Transport Verkehr AG, and included companies, such as Procter & Gamble and Poste italiane, as well as universities and technical institutes, such as École Polytechnique Fédérale de Lausanne and Technische Universität Berlin. The project has also received funding by the European Commission, through the Seventh Framework Programme (FP7). The project also received support from ALICE, a European Technology Platform (ETP) that will be discussed within this section.

The objective of this project was to apply the Physical Internet concept in a real case in the Fast-Moving Consumer Goods (FMCG) sector and contribute to the development of interconnected logistics at the European level.

The goal of the Modulushca project was to enable operating with developed ISO-modular logistics units of sizes adequate for real modal and co-modal flows of FMCG.

The project integrated a number of interrelated working fields: the development of a vision addressing the user needs for interconnected logistics in the FMCG domain; the development of a set of exchangeable ISO-modular logistics units providing a building block of smaller units; the establishment of digital interconnectivity of the units; and finally the development of an interconnected logistics operations platform leading to a significant reduction in costs and carbon dioxide emissions. The project demonstrated all the above in two implementation pilots for interconnected solutions (MODULUSHCA, 2012). Finally, the project also defined a roadmap to 2030 interconnected FMCG logistics, focusing on the physical, digital, operational and business interconnectivity (MODULUSHCA, 2016).

The International Physical Internet Initiative also initiated the International Physical Internet Conferences series. The conferences have been hosted so far by Université Laval (2014), by MINES ParisTech (2015) and by Georgia Tech (Physical Internet Center, 2016). The scientific interest for the Physical Internet has also been showcased
by many other conferences, such as the Information Systems, Logistics and Supply Chain Conference 2016 and the 6th European Transport Research Conference.

**ETP ALICE**

The Alliance for Logistics Innovation through Collaboration in Europe (www.etp-logistics.eu), also known as ALICE, is the European Technology Platform on Logistics. Its mission is to contribute to the development of new logistics and supply chain concepts and innovation for a more competitive and sustainable industry. The ambition is to contribute to a 30% improvement of end to end logistics performance by 2030. The ETP on logistics aims to accelerate the deployment of more efficient, competitive and sustainable supply chains. To accomplish this mission the ETP is bringing together as primary stakeholders: shippers and logistics service providers, as well as other relevant stakeholders including but not limited to: transport companies, terminal operators, support industries (Finance, ICT, Equipment/vehicle/vessel manufacturers, infrastructure providers, inspections), other ETPs and research and education institutions to (ETP ALICE, 2015):

- Define research and innovation strategies, roadmaps and priorities agreed by all stakeholders to achieve the ETP on Logistics vision.
- Foster innovation in logistics and supply chains, stimulating and accelerating innovation adoption in order to make possible the growth of the European economy through competitive and sustainable logistics.
- Raise the profile and understanding of new logistics technologies and business processes, monitoring progress and adjusting research and innovation roadmaps accordingly.
- Contribute to a better alignment and coordination of European, national, regional innovation programs in logistics.
- Provide a network for interdisciplinary collaborative research involving industry, academia and public institutions.

ALICE already boasts an impressive list of members, including companies such as Procter & Gamble, Mondelez, Ford and Volvo; terminal operators such as Amsterdam
Airport Schiphol and the port of Rotterdam alongside numerous universities research and research institutes (ETP ALICE, 2016).

ALICE is divided in five Working Groups, each one focusing on a specific field. The Working Groups, and their respective visions, missions and roadmaps are the following (ETP ALICE, 2016):

1. Sustainable, Safe and Secure Supply Chain

The Working Group vision and mission is achieving sustainable, safe and secure logistics systems and supply chains providing an answer to the growing concern on environmental and social problems related to logistics and security while maintaining or enhancing profitability.

This requires fully integrated close loop supply networks, in which logistic service providers, shippers and authorities closely cooperate. In particular shippers, as the owners of the goods in transit, play a key role; their decisions on product configuration after all determine what to transport.

The Working Group’s roadmap has the following milestones:

- 2020: Full alignment of economics, environmental, social and security goals
- 2030: Integrated decision making in end-to-end supply chain
- 2040: Safe and secure supply chains for circular economy
- 2050: Physical Internet

2. Corridors, Hubs and Synchromodality

The vision of the Working Group is EU wide synchromodal services for a smart and seamless network, based on corridors and hubs facilitating efficient operations and resilient, customized, responsive supply chains.

Its mission is to identify and define research and innovation challenges to establish a European core freight network of hubs and corridors bearing the emerging needs of the transport industries for a sustainable supply-chain.
In addition to the current focus on strategic investments and policies, the new focus of innovations should also include the integration of networks, the integration of services and the improvement of synergetic supply chains and transport.

The Working Group’s roadmap has the following milestones:

- 2020: Hub and network integration
- 2030: Innovative supply chain design and synchromodal service integration
- 2040: Synchromodal services door to door
- 2050: Physical Internet

3. Information Systems for Interconnected Logistics

The vision of this Working Group is to provide real-time re-configurable supply chains in supply chain networks with available and affordable ICT solutions for all types of companies and participants, regardless of size.

Its mission is to identify and define research and innovation challenges including the development of technologies and tools that facilitate the closure of existing gaps in current ICT systems and data sharing capabilities in supply chains for optimal performance in the execution of supply chain activities.

The Working Group’s roadmap has the following milestones:

- 2020: Interoperability between networks and ICT applications for logistics
- 2030: Full visibility throughout the supply chain
- 2040: Fully functional and operating open logistics networks
- 2050: Physical Internet

4. Global Supply Network Coordination and Collaboration

The vision of this Working Group is to realize supply networks that are operated as a whole, meaning full vertical and horizontal integration and coordination.

Its mission is to: i) remove barriers through new concepts and approaches, for closer vertical and horizontal collaboration among different network owners in Europe. ii) favor a smooth transition from independent supply chains to open global supply
networks. iii) make the most efficient use of available resources and modes, they will be compatible, accessible and easily interconnected.

The Working Group’s roadmap has the following milestones:

- 2020: Horizontal Collaboration
- 2030: Integration Manufacturing Logistics
- 2040: Open Supply networks
- 2050: Physical Internet

5. Urban Logistics

The vision of this Working Group is to achieve full integration of freight flows in cities operations and activities that allow citizens to access the goods and the goods to access the citizens they require and at the same time supporting sustainable development in cities.

Its mission is to identify and define research and innovation challenges to optimize flows of goods within, into and from urban conglomerates by leveraging existing infrastructure.

The Working Group’s roadmap has the following milestones:

- 2020: Defining and assessing new opportunities and business models
- 2030: Efficient and automated distribution systems
- 2040: Sustainable and integrated urban logistics in the city mobility system
- 2050: Physical Internet

As evident from the five roadmaps, the aims of the five Working Groups converge in the creation of the Physical Internet by 2050. Figure 3-4 depicts the five roadmaps of ALICE.

More than thirty projects and research studies have already been carried out, in Europe, to reach the goals described by ALICE (2014). A selection of five of them will be briefly presented below, one for each of the Working Groups / research topics.
The CORE Project

The CORE (Consistently Optimized Resilient Secure Global Supply Chains) project, is demonstrating how a powerful and innovative consistently optimized resilient ecosystem implementation, integrating interoperability, security, resilience and real-time optimization can produce cost effective, fast and robust solutions that will guarantee the efficient and secure transit of goods through the worldwide global supply chain system.

CORE is showing how protecting and securing the global supply chain, and reducing its vulnerability to disruption, whether caused by natural disasters, terrorism
or other forms of undesirable or illegal activity, can be done while guaranteeing the promotion of a timely and efficient flow of legitimate commerce through the EU and around the world. CORE is also demonstrate that this can be done while at the same time offering tangible benefits to involved stakeholders, thus facilitating its adoption by commercial entities (CORE, 2015).

The TIGER Project

The TIGER (Territorial Impact of Globalization for Europe and its Regions) Project, addressed the issues of promoting sustainable logistics introducing innovative railway services connecting the sea ports of the EU with the Hinterland. This was done with particular attention to the flows generated to/from the Far East and South East Asia, involving all major European ports, suffering from traffic congestion. In particular, two North European, and three Mediterranean ports were key actors in researching innovative logistics solutions in TIGER. The inland distributions to/from the ports was completely restructured. New production concepts based on ship to train operations together with shuttle trains prosecution into inland dry ports, were adopted. By doing so, dry ports constituted a sizeable extension of the yards, since they were capable of executing any customs, handling and ancillary operations, up to delivery to final destinations. Such service restructuring has been achieved through substantial investments in ports/dry ports infrastructures, handling equipment, technology innovations, new intelligent management systems, modern production processes, and lengthening of the total value chain to/from the dry ports up to the end users (TIGER, 2014).

Through TIGER, a coherent set, of innovative production cycles delivered better service, greater performances and faster transit times at a considerably reduced costs. These were the prerequisites for modal shift in favor of rail freight. Whilst TIGER was developed up to the pilot test phase, Tiger Demo accompanied the pilots, turning them into full scale demonstrators, fine tuning the service performance (TIGER, 2014).

The COMCIS Project

COMCIS (Collaborative information services for container management), is a collaborative project between multiple transport and logistics actors that improved
situational awareness along global supply chains in support of enhanced logistics services (COMCIS, 2014).

The first objective was to demonstrate end-to-end transport chain, whereby enabling more flexibility on the exact hinterland operations finally chosen to reach the final destination. The integration of information from the various legs (services) created optimal visibility, alignment between subsequent legs, pro-active rescheduling and personalized event management.

The second objective was the enabling of data exchange according to a common framework. In order to do so, the team used connectors that translate a variety of message types that were part of pre-existing standards to the messages within the common framework. Such connectors make use of the ontological approach in the e-Freight project through which a systematic mapping onto the common framework message formats has been defined and executed.

The third objective was to integrate compliance and customs facilitation. In order to do so, the team used consignment information from shippers and forwarders in order to capture more reliable cargo details that support the risk assessment process by customs.

The fourth objective was about demonstrating systems collaboration by creating interoperability between ICT systems that had originated from previous projects and about how the common framework ensures this interoperability.

The potential of these integrated solutions across a wide range of situations was showcased by real implementations, notably with DHL Global Forwarding and Europe Container Terminals (COMCIS, 2014).

*The iCargo Project*

The iCargo (Intelligent Cargo in Efficient and Sustainable Global Logistics Operations) Project, advanced and extended the use of ICT to support logistics services that: (i) synchronize vehicle movements and logistics operations across various modes and actors to lower carbon dioxide emissions (ii) Adapt to changing conditions through dynamic planning methods involving intelligent cargo, vehicle and infrastructure
systems and (iii) Combine services, resources and information from different stakeholders, taking part in an open freight management ecosystem (iCargo, 2016).

To achieve these targets, iCargo designed and implemented a decentralized ICT infrastructure allowing real world objects, planning services including carbon dioxide calculation capabilities and existing systems to co-exist and efficiently co-operate at an affordable cost for logistics stakeholders.

The iCargo infrastructure includes Intelligent Cargo items to facilitate reactive decision-making and to integrate information obtained from on-going execution into planning processes to optimize environmental performances, including real-time information about traffic and transport infrastructure conditions.

iCargo involved representatives of the main stakeholders in three main areas of activity: (i) research and technological development, involving leading ICT companies and institutes that integrated in iCargo the necessary technology components, including results from related EU projects, and developed innovative approaches and business models for co-modal transport environmental optimization and dynamic planning; (ii) implementation, demonstration and validation of three extensive pilots in end-to-end multi-actor intermodal chains, involving users from logistics companies, shippers and public authorities and (iii) extensive dissemination of research results, demonstration and pilot cases validation activities, aimed at transferring iCargo results to the international transport logistics community and supporting take-up and extensive exploitation that began immediately after the project (iCargo, 2016).

The FREVUE Project

FREVUE (Freight Electric Vehicles in Urban Europe) is currently demonstrating in eight major European cities that electric vehicles (EVs) operating “last mile” freight movements in urban centers can offer significant and achievable decarburization of the transport system. Demonstrators are being deployed in Amsterdam, Lisbon, London, Madrid, Milan, Oslo, Rotterdam and Stockholm. The demonstrators have been designed to ensure FREVUE covers the breadth of urban freight applications which occur across Europe. By exposing 127 electric vehicles to the day to day rigors of the urban logistics environment, the project will prove that the current generation of large electric vans and trucks can offer a viable alternative to diesel vehicles - particularly
when combined with state of the art urban logistics applications, innovative logistics management software, and with well-designed local policy (FREVUE, 2014).

The project is also demonstrating solutions to the barriers currently inhibiting uptake of EVs in the sector and includes leading European researchers who working on a common pan-European assessment framework to understand the impacts of these solutions. This ensures that the project creates a valuable European evidence base on the role of EVs in urban logistics. Partners are producing a detailed White Paper on the feasibility of EV rollout in logistics across Europe, with chapters containing best practice advice on EV in logistics for: policy makers, logistics operators, their customers and companies developing technology to support the sector (FREVUE, 2014).

The final overarching objective is to encourage the exploitation of these best practice results through a targeted dissemination campaign aimed at decision makers in the logistics industry. To complement this, FREVUE will also create a network of “Phase 2” cities to directly share the lessons learned from the demonstrators. These cities are expected to be the first cities to expand the successful concepts developed by FREVUE (2014).

All five projects selected here have received funding under the Seventh Framework Programme of the European Commission and most of them have already been completed. New projects are currently under various stages of development in Europe, notably under Horizon 2020 (CORDIS, 2016), and more are expected to be launched in the near future.

Concluding this chapter, it is important to stress that research and development in logistics and supply chain management is moving fast. Both inside and outside the scope of the Physical Internet related efforts described in this section, shippers and logistics service providers such as Procter & Gamble, DHL, and Kuehne & Nagel, as well as local and national authorities are also establishing their own research and development centers and initiatives for logistics and supply chain management (ETP ALICE, 2013). These are providing solutions that could be useful for the implementation and development of the Physical Internet.
Yet, the broad variety of stakeholders intervening in logistics and supply chain management leaves the sector, and the relevant research, too fragmented to be efficient. As a result, there has been a lack of paramount vision on the work done and important overarching logistics topics are often left untreated. (ETP ALICE, 2016)

This is why initiatives and platforms, such as ALICE and the International Physical Internet Initiative, are important. They provide the much needed overarching and meta-systemic vision that transcends projects, organizations and local and national authorities, fostering alignment and coordination between the research and development efforts of the various stakeholders. Fortunately, the importance of this holistic view of logistics appears to be increasingly recognized.
Chapter 4. Designing Network Protocols for the Physical Internet

In this chapter we will introduce a number of network protocols designed for the Physical Internet. In that light, a broad, theoretical comparison between computer and logistics internetworks is initially made. This venture produces some early insights into the potential needs of the Physical Internet. These insights are consequently incorporated into the design of a reference model. Finally, based on this reference model, a stack of three network protocols is introduced, attempting to optimize the end-to-end delivery of products.

4.1 Analogies and Contrasts between Computer and Logistics Internetworks

Contemporary logistics networks are evolving without macroscopic coordination or extensive collaboration, usually overlapping each other geographically. As a result, these private networks are usually intertwined, yet largely independent and often heterogeneous, in spite of their entangled flows and shared use of public infrastructure, such as highways. This independence of logistics networks leads to inefficiency through the suboptimal use of various types of means, ranging from warehouses to trucks, which are typically dedicated to a single organization or a small number of customers (Stefanovic & Stefanovic, 2008; Sarraj, et al., 2014).

Decades ago, computer networks were in a similar situation. Drastically summarized, computers had evolved rapidly from being few, cumbersome and isolated to being relatively small and often linked by private networks, with their numbers growing exponentially as they were increasingly adopted by businesses and private users. Most authorities in the field agreed that the paradigm was very inefficient and macroscopic solutions were needed. During the search for a way to conceptualize how computer networks should be transformed, a physically inspired transport and logistics metaphor emerged: building the information highway (Montreuil, 2011).

Computer networks are thriving in this highly interconnected, paradigm. The transition reshaped completely the structure of computer networks, predominantly into
the Digital Internet, revolutionizing both the economic and social reality. As we have already seen, at the core of the paradigm shift is the building of an open distributed network infrastructure, enabling the interconnection between networks in a way transparent to the user, allowing the transmission of formatted data packets in a standard way, permitting them to transit through heterogeneous equipment respecting certain protocols. (Montreuil, 2011; Tanenbaum & Wetherall, 2011).

This paradigm shift is the main source of inspiration for the Physical Internet. The Physical Internet envisions a shift from private, overlapping yet uncoordinated logistics networks to an open distributed network infrastructure, enabling the interconnection between networks in a way transparent to the user, allowing the transmission of formatted physical packets, called \(\pi\)-containers, in a standard way permitting them to transit through heterogeneous equipment respecting certain protocols (Montreuil, 2011; Montreuil, et al., 2012).

The strong similarity between the two paradigms opens up the possibility of borrowing, or even transposing concepts between them. At the current, early stages of envisioning and experimentation with the design of the Physical Internet, drawing analogies from the Digital Internet can be very helpful. This is due to the assumption that in similar networks, similar problems may arise. So, in our case the Digital Internet is the obvious source of inspiration for solutions.

These analogies can be drawn in a variety of concepts and structures throughout both paradigms and there may be more than one interpretation. According to Sarraj et al. (2014) there are three main analogies:

1. The interconnection of networks

As we have already discussed, the Digital Internet is a network of networks operated by Internet Service Providers. Standardized data packets are transferred between these networks by routers. During an exchange between distant hosts, these data packets will sequentially pass, usually via cable, through several networks and consequently through several switches and routers (Tanenbaum & Wetherall, 2011).

Similarly, the Physical Internet is a network of networks, operated by Logistics Service Providers. \(\Pi\)-containers are transferred between these networks by \(\pi\)-hubs.
During a delivery to a distant customer’s store, these π-containers will sequentially pass, via truck, ship or any other mode, through several networks and consequently through several π-nodes (Montreuil, 2011).

As it is visible from the last two paragraphs, a direct analogy emerges, with the basic functions for the interconnection of computer networks into the Digital Internet being effectively transposed for the interconnection of logistics networks into the Physical Internet.

The basic unit of flow in the Digital Internet is the data packet, also known as datagram, which functions as a form of encapsulation for the data. Similarly, the basic unit of flow in the Physical Internet is the π-container, encapsulating physical products. These units of flow have to be assembled and disassembled at the initial and final nodes respectively. This is done by the sending and receiving hosts in the Digital Internet. In the Physical Internet the initial node is a supplier and the final node is a customer, both of which can be replaced by π-gates if the products are coming from suppliers or going to customers outside the Physical Internet. Of course other π-nodes may also play the roles of a supplier or a customer, and these roles are not mutually exclusive or static, just as the sending and receiving hosts in the Digital Internet may switch roles at any time. The intermediate nodes in the Digital Internet are switches and routers, forwarding data packets within and between networks respectively. The basic function of routers, forwarding between networks, is performed by π-hubs in the Physical Internet. The forwarding within the networks is done by a variety of π-nodes. Finally, the arcs of the networks that enable the transport of the units in the Digital Internet are usually cables, most notably optical fiber cables, or even the air, in short distances. The Physical Internet is enabled by arcs of transport services of various modes, including truck, train, ship and many more (Montreuil, 2011; Sarraj, et al., 2014).

2. The structure of the network of networks.

In the Digital Internet every node is able to connect with any other node, as this is technically defining a network. We have seen that this does not mean that there is an arc directly connecting every node to every other node of the internetwork, as it would be a waste of resources, so a “fractal” architecture has been predominant instead. The interconnection of heterogeneous networks is enabled by the presence of protocols that
are respected throughout the internetwork. Again as we have seen, this does not mean that the whole internetwork is either operated or regulated a single entity (Tanenbaum & Wetherall, 2011; Sarraj, et al., 2014). A group of networks and routers controlled by a single administrative authority is called an autonomous system, a concept primarily used for the purpose of routing (Comer, 2000). A similar conceptual structure is expected to emerge in the Physical Internet.

As the Digital Internet is divided in Autonomous Systems, usually operated by Internet Service Providers. The Physical Internet may also be divided in Autonomous Systems, operated by Logistics Service Providers. Even in the highly interconnected and collaborative paradigms that we examine, the Autonomous Systems may be geographically overlapping and operating concurrently while they are managed by independent entities. These entities, operating the various Autonomous Systems typically are not representing sovereign authorities. This means that there is another level of division of the internetworks, that of zones of sovereignty. These zones of sovereignty are usually states and they have the power to impose certain regulations (Tanenbaum & Wetherall, 2011; Montreuil, 2011; Sarraj, et al., 2014). Although the regulations that will be imposed on the Physical Internet can only be speculated, examining those currently imposed on the Digital Internet, as well as those on logistics networks, would be very important to make educated prediction.

The Digital Autonomous Systems are interconnected through predetermined border routers (Tanenbaum & Wetherall, 2011). Physical Autonomous Systems could similarly decide to use only certain of their π-nodes, namely π-hubs, as interconnection points, in order to avoid overcommitting resources and to facilitate the management of operations and the implementation of policies. This is similar to the function currently performed by customs, so, since zones of sovereignty and Autonomous Systems are distinct this part of the analogy is relatively week. If Physical Autonomous Systems are operated by agencies of sovereign states, then this part of the analogy could be more important with certain π-nodes evolving into a form that could incorporate characteristics of both border routers and customs.
3. The Routing Operation

The routing of data packets in the Digital Internet is enabled through routing tables, located in routers and hosts, and destination addresses which are part of the packet’s control information (Comer, 2000). Similarly, the routing of π-containers in the Physical Internet could be enabled through routing tables located in π-nodes and destination addresses which are part of the π-containers’ control information.

Data packets consist of bits and are conceptually separated into control information, located in the packet’s header and trailer, and user data, also known as payload. The destination address is part of the control information included in a data packet’s header. When a data packet is initially forwarded by the sending host or arrives at a router its destination address is checked, and the data packet is forwarded according to the routing table of this host or router (Comer, 2000; Tanenbaum & Wetherall, 2011).

Π-containers could be similarly conceptually separated into digital control information and physical payload. The destination address is part of the control information included in a π-container’s header. Whether the path to reach the destination will also be part of the control information is unclear at this moment. One approach, very similar to that of the Digital Internet would be for the π-container to be forwarder according to a π-node’s routing table to the next π-node, so that the path is effectively decided one step at a time. Another approach is that the π-container’s path is determined at the beginning. The latter approach departs considerably from the typical operation of the Digital Internet, yet it appears to be suitable as all the stakeholders would presumably benefit from the early knowledge of the path. Of course, a compromise between the two approaches may also be attempted.

In both cases, however, the routing is determined on the basis of pre-established criteria and policies about the preferred path to the destination. The difference lays on which stakeholder selects these criteria and policies. In any case, the construction and updating of a routing tables is fairly complicated (Comer, 2000). This is a field where transposition of protocols from the Digital Internet could help to accelerate the development of the Physical Internet. Of course, the criteria and policies should be different, with metrics such as transport cost and carbon dioxide emissions becoming relevant.
Having discussed the major analogies between computer and logistics internetworks, it is important to investigate what the contrasts between them are. This is a crucial step in concluding which analogies are valid and useful in the creation of the Physical Internet.

Four fundamental differences can be defined as the core of the contrast. First, the movement and the operations in the Physical Internet are time-consuming. Although, the time requirements for moving and operating on $\pi$-containers is expected to drop over time, it is impossible to become comparable to the almost instantaneous movement and operations of data packets. Second, every move or sojourn of a $\pi$-container and every physical operation on it is costly. Again, the costs are expected to drop substantially over time but it is impossible to become comparable to the costs of moving, storing and operating on data packets (Montreuil, 2011). Third, in contrast to the bits forming the payload of a data packet, the payload contained in a $\pi$-container is valuable and cannot be instantly and freely reproduced. Fourth, $\pi$-containers have physical payloads and digital control information. This duality is in contrast to the completely digital nature of data packets.

A number of differences between the Digital and Physical Internet, regarding their operation, stem from these four fundamental differences. These operational differences are partly a product of speculation, since they cannot be scientifically assessed before the new paradigm is implemented. Four of them are described here, standing out as both very important and likely.

Maybe the most important operational difference is the much more researched and optimized planning ability that the Physical Internet can afford. While $\pi$-containers are moving or undergoing operations, their control information can move ahead of them and undergo operations in negligible time. Also, the moving and operating of their digital control information can be done at costs that are negligible when compared to the moving and operating of the $\pi$-containers. These two facts open up possibilities for research and optimization in the Physical Internet that would be terribly resource inefficient in the Digital Internet. A further consequence is that, in contrast to the Digital Internet, tracking and routing becomes separate from the arrival to a node of the network. The ability for en route tracking will presumably increase the transparency of the internetwork. The ability for en route decision making is likely to lead to different
dynamics between the various stakeholders. The operators of the nodes may have a less active decision making role in the Physical Internet, with this role being potentially transferred to another stakeholder such as the operator of the network’s arcs, namely a transport service provider, the sender, the receiver or even to a new kind of stakeholder dedicated to routing optimization and regulation.

Another major operational difference between the Digital and the Physical Internet stems from the fact that the payload of a π-container is valuable and cannot be instantly reproduced, in contrast to the payload of a data packet. Consequently, methods, such as multicasting, that include the reception of a single packet and then the forwarding of multiple copies of the packet cannot be conceivably transposed to the Physical Internet. The functioning of the Digital Internet also incorporates the discarding or loss of packets in ways that would be unacceptable in the Physical Internet. Therefore, reliability will be a much higher priority in the internetwork and many important functions of the Digital Internet, notably those using the loss of packets as an indicator, cannot be transposed on the Physical Internet (Tanenbaum & Wetherall, 2011). This could lead to the building of fundamentally different methods to achieve the needed functions or the use of methods similar to those used in the Digital Internet on a digital level, decoupled with the movement of π-containers.

Another major operational difference is related to the internetworks’ arcs. In the Digital Internet the decision to forward a data packet directly from node A to node B is sufficient when the two nodes are connected by an arc. In the Physical Internet this decision alone will be insufficient. This is due to the multiple arcs potentially directly connecting two nodes, as each arc represents one transport service. This ability to choose from multiple arcs will allow for further optimization but it will also require further planning. It is also expected to encourage competition between transport service providers. It is worth mentioning as a side note that the inclusion of multiple arcs/transport services into the standard operation of the Physical Internet is expected to enhance the development of intermodal transport systems.

The last major operational difference defined here is the role of the nodes. Since π-containers cannot be moved instantaneously, like their digital counterparts can, there is a need for storage near their destination or along their way there. This storage or
sojourn, itself a costly operation, is expected to be done in \( \pi \)-nodes. In the Digital Internet the routers and switches that form the nodes of the internetwork are not expected to store data packets. This storage is expected to be done by hosts, including the sender, the receiver or a cloud storage host. As a result, in spite of the similarities in the structure of both internetworks, most \( \pi \)-nodes are expected to operate in analogy to both routers and hosts, rather than just to routers. Again, this could lead to different dynamics between the various stakeholders in the two paradigms. The operators of \( \pi \)-nodes would need to invest in both functions simultaneously, making the investment much more expensive but also making the operators controlling a bigger proportion of the internetwork’s functionality. The combination of these two conditions could potentially be dangerous as relatively few investors could control very big parts of the Physical Internet. This should be taken into account when designing the structure of the emerging internetwork, so as to encourage competition.

After examining both the analogies and contrasts between the Digital Internet and the emerging Physical Internet, it is visible that there are very strong similarities, yet there are fundamental differences that prevent an integral transposition. As a consequence the protocols proposed in this chapter are not directly correlated to those of the Digital Internet. Yet, the Digital Internet, has been a major source of inspiration for the design of the protocols described in the rest of the chapter, with the borrowed concepts being coupled with conventional logistics operations, creating a novel and potentially much more sustainable design for the industry.

4.2 A Reference Model for the Physical Internet

As established in the previous section, the integral transposition of Digital Internet concepts to the proposed Physical Internet is not advisable due to their fundamental differences. It has also been established, however, that the Digital Internet can be a very valuable source of inspiration.

The most important inspiration lays in the introduction of a stack of layers providing guidelines for the design of network protocols. The motivation for taking this approach to logistics internetworks is the same as for computer internetworks. It is a way of hiding the implementation details of a particular set of functionalities and allowing the
separation of concerns to facilitate interoperability and platform independence. Practically, this modularity makes the design and evaluation of individual protocols easier, while allowing for their replacement without interrupting the rest of the network architecture. Although potential security concerns are not addressed here, the layered approach can also facilitate the introduction of security mechanisms in future updates.

In contrast, however, to the Digital Internet, the protocols of the Physical Internet, as defined here, are sets of rules primarily concerned with the specifics of decision-making procedures. They are not concerned with not with the interactions between peers. In fact, the very concept of peers does not exist in the proposed design.

The overall stack has the purpose of enabling optimized decisions throughout the logistics industry, effectively optimizing the end-to-end delivery of products. In doing so, three conceptual layers have been proposed, along the lines of the three major, conceptually separated, problems: the containerization, the routing and the delivery.

Before proceeding with the description of the layers, it should be clarified that the aforementioned problems are solved with the topology of the internetwork being considered as a given. The arcs in the topology of the Physical Internet are transport services and they are considered predetermined, similarly to the arcs of the Digital Internet. If the optimal solution given by the protocols is not deemed acceptable by the user and ad hoc transport services need to be established as a result, this should be done outside this framework. Then, after the new transport services are established and the system has been updated, the protocols can be rerun.

The protocol of the containerization layer has to specify the assignment of outbound products to a single or in multiple \( \pi \)-containers, the sizes of these \( \pi \)-containers and the cost of the relevant process while maintaining the cost at a minimum. In doing so, it needs input concerning the number of the outbound products and the dimensions and weight of a single unit of these products. The output, similar to the concept of service in the Digital Internet, it provides to the routing layer protocol consists of the type/size of each \( \pi \)-container and its total cost up to this point, which is presumably equal to its containerization cost.

The protocol of the routing layer uses the received input to make rooting decisions in the internetwork of \( \pi \)-nodes and transport services/arcs that compose the Physical
Internet. The output it provides consists of the Estimated Time of Arrival (ETA) to the last π-node and the total cost until the π-container has been received by this π-node.

The protocol of the distribution layer has to enable the last mile delivery from the last π-node to the final destination, completing the end-to-end delivery of the π-container. If the final destination is the last π-node, instead of a retail store, the distribution protocol may be skipped. The output it produces consists of the ETA to the final destination and the total cost until the π-container has been received by the destination, which is effectively the total cost of the end-to-end delivery.

As it can be understood, in order to use any of the protocols of the layers some initial information is needed. This has created the need for a user interface, where the details about the order will be inserted. This could be an application “running on top” of the protocol stack or, potentially, another layer in the stack. Here, the former approach has been selected. The needed information should include the number of outbound products, the dimensions and weight of a single unit of the product, the address of the destination and the estimated cost of delay per hour. The application should be able to automatically assign the delivery to the π-node that serves the area where the destination is located. In the future, as the Physical Internet will emerge, updated versions of the user interface application may include more information, in accord to the potentially growing needs of the protocols regarding details about the deliveries. Finally, the application should be able to receive the results, effectively the output of either the distribution or the routing layer protocol, and present it to the user.

The aforementioned application is concerned with the input provided by the user, yet there are many more parameters that need to be known about the state of the Physical Internet. Data aggregation is crucial to make informed decisions. A platform containing all the known information about the state of the Physical Internet at any given time has to be established, presumably in the form of a metasearch engine rather than a single database. The type of information needed is protocol-specific, so once a protocol changes, the needed information may also change. Also, the Physical Internet is expected to be consisted of heterogeneous networks which in turn may be providing different types of information. This is a very interesting problem that cannot be solved at this stage. We can speculate, however, that it will be solved partially by a metasearch
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engine and partially by the implementation of different protocols by heterogeneous networks.

![Diagram of the proposed reference model for the Physical Internet.](image)

*Figure 5: The proposed reference model for the Physical Internet.*

Having established the reference model, depicted in Figure 4-1, providing guidelines for the design of network protocols, the next sections propose a set of three of these protocols.

4.3 A Containerization Protocol

A containerization protocol for the Physical Internet has to specify the assignment of outbound products to a single or in multiple π-containers, the sizes of these π-containers and the cost of the relevant process. Other parameters, such as the appropriate safety and security measures and temperature range could be added in later versions of the protocol. If these added parameters are to be included, it should be taken into account that the output provided to the next layer only includes the types/sizes of the outbound π-containers and the cost of their containerization process, so any additional features of the π-containers will be ignored by the next protocol.
A containerization protocol should be applied when the products are entering the Physical Internet. This could be either in plants, compatible to the Physical Internet, or in any other node that is acting as a π-gateway. This is an essential assumption since the Physical Internet only handles π-containers. Any part of the internetwork not dedicated to π-containers is not, strictly speaking, part of the Physical Internet (Montreuil, 2011).

The development of a set of π-containers for the Physical Internet, with standardized sizes, interfaces and functionalities, is an interesting and challenging task beyond the scope of this diploma thesis. Lacking this, we use as a realistic starting base the recently introduced 40-foot pallet-wide container (Bouley, 2010), which has the following dimensions: 12 m × 2.4 m × 2.4 m. As Sarraj et al. (2014) have suggested, and applied in their simulations, the π-containers may have the following sizes: {1.2, 2.4, 3.6, 4.8, 6, 12} m × 2.4 m × 2.4 m, starting with π-containers a tenth of the 40-foot pallet-wide container’s length and progressing up to π-containers with the full 12 m length. Their width and height remain the same so that they are compatible with pallet-wide containers and the various modes of transport such as ships, trains and trailer trucks. It is assumed that their internal volume can be fully used. These sizes are primarily suggested for relatively large shipments to destinations such as distribution centers, not for smaller shipments to retail stores.

To address this shortcoming, and in anticipation of a standardized set of sizes, a new conceptual π-container is introduced here, in addition to the aforementioned set. This π-container has the following dimensions: 1.2 m × 0.8 m × 0.8 m. This size has been selected in order to satisfy needs similar to those currently addressed by the use of European pallets, that have an area of 1.2 × 0.8 m² (European Pallet Association, 2016). The height has been selected so that it takes advantage of unitary π-containers’ ability to form composite π-containers. The height of pallets is usually larger than 0.8 m but it has been chosen to accommodate the need for relatively small π-container compatible with the needs of retail stores. It should be noted here that this size selection benefits from the assumption that these relatively new small π-containers can be opened and handled without need for big or particularly expensive equipment. If this is not the case, their use would be limited.
Returning to the proposed Containerization Protocol, the needed inputs, potentially provided by another layer, are the dimensions of a single unit of the product and the total number of the outbound units. An assumption is made here that each \(\pi\)-container is filled with a single or multiple units of one and only one type of product. This assumption is in accordance with what empirically appears to be the standard business practice and allows for the easier future introduction of further product-specific parameters. The service that the Containerization Protocol provides to the next protocol, as it has already been mentioned, is the number of outbound \(\pi\)-containers and their sizes.

It is also assumed that all units will be placed inside the \(\pi\)-container in the same way. This assumption may lead in some cases to suboptimal results, but it has been made because many products are designed to stand or travel on a predetermined side. Attempting to further improve the ratio of units per container could make units be placed standing on different sides, potentially leading to them being damaged during the travel and making their de-containerization and handling harder to automatize.

The protocol is implemented through the following algorithm:

**Assumptions**

a) The Physical Internet only handles \(\pi\)-containers, not products. Therefore, once containerized, the products will stay inside the \(\pi\)-containers until they reach their final destination.

b) Each \(\pi\)-container is filled with a single or multiple units of one and only one type of product.

c) Products are placed inside \(\pi\)-containers in a standard position.

d) The full dimensions of the \(\pi\)-container can be used.

**Notations**

Index:

\(\alpha\) The axes of a three-dimensional Cartesian coordinate system, including \((x), (y)\) and \((z)\).
Input:

NP  The number of outbound products.

DP_α  The dimensions of a unit of the outbound products, represented along the three axes “α” of the Cartesian coordinate system.

WP  The weight of a unit of the outbound products.

Parameters:

TV  The total volume of the outbound products.

TW  The total weight of the outbound products.

DC_{π}\_α  The dimensions of a “π” type π-container, represented along the three axes “α” of the Cartesian coordinate system.

W^{(π)}  The maximum weight of a “π” type π-container.

CC^{(π)}  The containerization cost of a “π” type π-container.

PC^{(π)}  Number of products in a π-container.

Variable:

θ^{(π)}  Binary decision variable indicates whether a “π” type π-container will be selected.

Output:

π  The type of the outbound π-container, including 1.2 m × 0.8 m × 0.8 m (πα), 1.2m × 2.4 m × 2.4 m (πβ), 2.4 m × 2.4 m × 2.4m (πγ), 3.6m × 2.4 m × 2.4 m (πδ), 4.8m × 2.4 m × 2.4 m (πε), 6m × 2.4 m × 2.4 m (πζ), 12m × 2.4 m × 2.4 m (πη).

TC  The total cost for the outbound π-container.
Formulation

Step 1. Require input, including the number of products “NP” and the dimensions and weight of a unit of the product “DP\_a” and “WP” respectively.

Step 2. Initialize:

\[ TC = 0 \] (1)

Step 3. Set:

\[ TV = NP \cdot \prod_{a \in \{x,y,z\}} DP_a \] (2)

\[ TW = NP \cdot WP \] (3)

Step 4. If \( DP_x > DC^\pi_x \) \& \( DP_y > DC^\pi_y \) \& \( DP_z > DC^\pi_z \), \( a \in \{x,y\} \) STOP.

Step 5. If \( WP \geq W^\pi \) STOP

Step 6. If \( TV \geq \prod_{a \in \{x,y,z\}} DC^\pi_a \) set \( \pi = \pi \eta \) and go to Step 8.

Step 7. Objective function:

\[ MinZ = \prod_{a \in \{x,y,z\}} \theta^{(\pi)} DC^\pi_a, \forall \pi \in \{\pi\alpha, \pi\beta, \pi\gamma, \pi\delta, \pi\epsilon, \pi\zeta, \pi\eta\} \] (4)

Constraints:

\[ DC^\pi_x \geq DP_x \land DC^\pi_y \geq DP_y \land DC^\pi_z \geq DP_z, \forall a \in \{x,y\} \] (5)

\[ W^\pi \geq TW \] (6)

\[ \prod_{a \in \{x,y,z\}} DC^\pi_a \geq TV \] (7)

\[ \theta^{(\pi)} \in \{0,1\}, \forall \pi \in \{\pi\alpha, \pi\beta, \pi\gamma, \pi\delta, \pi\epsilon, \pi\zeta, \pi\eta\} \] (8)

\[ \sum_{\pi \in \{\pi\alpha, \pi\beta, \pi\gamma, \pi\delta, \pi\epsilon, \pi\zeta, \pi\eta\}} \theta^{(\pi)} = 1 \] (9)

Step 8. For the selected type of \( \pi \)-container “\pi”: 
$PC^{(\pi)} = \prod_{a \in \{x, y, z\}} DC_a^{(\pi)} \, divDP_a \quad (8)$

$TC = CC^{(\pi)} \quad (9)$

$NP^{(k+1)} = NP^{(k)} - PC^{(\pi)}, \quad k = 0, 1, \ldots \quad (10)$

**Step 9.** Forward the type of the $\pi$-container “$\pi$”, and its total cost “$TC$” to the routing layer.

**Step 10.** If $NP > 0$ go to Step 2. Otherwise STOP.

Equation (1) initializes the total cost for the outbound $\pi$-container. Equations (2) and (3) estimate the total volume and weight of the outbound products. Objective function (4) selects the smaller type of $\pi$-container, under the constraints (5) and (6) that establish the products can fit into the $\pi$-container and (7) that establishes the minimum number of $\pi$-containers will be used. Constraint (8) establishes “$\theta^{(\pi)}$” as a binary variable. Constraint (9) establishes that one and only one $\pi$-container will be selected. Equation (8) estimates the number of products fitting into the $\pi$-container. Equation (9) establishes the new total cost for the outbound $\pi$-container based on the selected type “$\pi$” of $\pi$-container. Equation (10) establishes the number of products not assigned yet to $\pi$-containers.

### 4.4 A Routing Protocol

A routing protocol makes routing decisions in the internetwork of $\pi$-nodes and transport services/arcs that compose the Physical Internet. The received input from the containerization layer includes only the type of the outbound $\pi$-container and total the cost up to this point. The output only includes the expected time needed to reach the destination $\pi$-node and the total cost until the $\pi$-container has been received by it.

The protocol is designed to optimize the shipment of products encapsulated into $\pi$-containers. It is not concerned with the scheduling of the relevant transport services or how the $\pi$-nodes operate internally. The needed parameters have to be known, a requirement that is a characteristic of the Physical Internet by definition (Montreuil, et al., 2012).
As the context of this work is mostly exploratory and the details regarding the structure and mode of operation of Physical Internet are yet to be developed there is considerable uncertainty. In that light, a number of assumptions have been made, building a more solid foundation on which the Routing Protocol is developed. However, as it has already been discussed, the protocols proposed here, similarly to their digital counterparts, can be updated or replaced in order to adapt to the reality of the Physical Internet, when it emerges.

The algorithm described below, concerning the protocol’s implementation and has been partially based on A*, a popular heuristic algorithm (Fu, et al., 2006) mostly used for transport optimization. This choice has been made in an attempt reduce the needed system resources and consequently accelerate the optimization process. Certain elements concerning the establishment of costs have also been borrowed by Behdani et al. (2014) who have built a very detailed model for synchromodal freight transport planning.

Assumptions

a) The model considers the transport between two directly connected π-nodes.
b) Every pair of two π-nodes has at least one transport service of at least one mode in any given day in order to be considered directly connected.
c) Before a delivery is scheduled, it was been established that the receiving π-node can receive its maximum volume and weight.
d) Five transport modes are considered in the model: (container and/or RORO) ship, airplane, barge, rail, and truck. There is only one route for each available transport mode on a single arc and there is no transfer between modes during transport. The service for different modes has different transport cost and waiting times in the terminal. If a transport mode is not available between two directly connected π-nodes a given day the relevant arc is not present.
e) All the parameters are visible in an open market of transport requesters and transport providers, enabled through the open live documentation of performance and capabilities (Montreuil, 2011; Montreuil, et al., 2012).
f) All π-nodes are constantly operational.
g) There are no unexpected delays or accidents.
Notations

Index:

- \(i,j\) Origin and destination nodes of a service.
- \(\gamma\) Geographic coordinates, including latitude (\(\varphi\)) and longitude (\(\lambda\)).
- \(m\) Transport modes of service, including ship (S), aircraft (A), barge (B), rail (R) and truck (T).
- \(l\) Number “\(l\)” service of different modes within a day; \(l \in \{1, \ldots, L_{ij}\}\). The service is defined here as a \(2.4 \, \text{m} \times 2.4 \, \text{m} \times 12 \, \text{m}\) shipment. A single departure of a mode may include multiple services.
- \(n\) The \(n^{\text{th}}\) day of the transport. \(n \in \{1, \ldots, N_{ij}\}\)
- \(\alpha\) The axes of a three-dimensional Cartesian coordinate system, including (x), (y) and (z).

Input:

- \(\pi\) The type of the outbound \(\pi\)-container. The included types of \(\pi\)-containers have been described in section 4.3.
- \(\text{TC}\) The total expenditures for the outbound \(\pi\)-container.
- \(f\) The destination \(\pi\)-node.

Parameters:

- \(C_{\gamma}^{(l)}\) The linear expression of “\(\gamma\)” of node “\(i\)”, in kilometers.
- \(\text{CK}_m\) The average cost of covering a kilometer by mode “\(m\)”.
- \(C_{\text{m}n}^{(\pi_{ij})}\) The cost of transporting a “\(\pi\)” type \(\pi\)-container from node “\(i\)” to node “\(j\)” by service “\(l\)” of mode “\(m\)” on day “\(n\)”.
- \(P\) An artificial parameter, representing the penalty of failing to deliver timely, divided by the hours from the order the agreed delivery time.
- \(\Omega^{(\pi)}\) The cost of sojourning a “\(\pi\)” type \(\pi\)-container at node “\(i\)” per hour.
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\( D_{mln}^{(ij)} \) The time of departure from node “i” of service “l” of mode “m” on day “n”.

\( C_{m}^{(mj)} \) The operating cost for a “\( \pi \)” type container arriving by mode “m” at node “j”.

\( AV_{mln}^{(ij)} \) The available volume of service “l” of mode “m” on day “n” from nodes “i” to node “j”.

\( W^{(\pi)} \) The maximum weight of a “\( \pi \)” type \( \pi \)-container.

\( AW_{mln}^{(ij)} \) The available weight of service “l” of mode “m” on day “n” from nodes “i” to node “j”.

\( HT_{m}^{(\pi j)} \) The handling time of a “\( \pi \)” type \( \pi \)-container arriving by mode “m” at node “i”.

\( TT_{mln}^{(ij)} \) The time needed for transport service “l” of mode “m” on day “n” to arrive to node “j” after departing from node “i”.

Variables:

\( F^{(j)} \) The artificial total cost to reach node “j”.

\( A^{(j)} \) The time of arrival at the destination node “j”.

\( K^{(j)} \) The position of node “j” within the paths sequence.

\( X_{mln}^{(mj)} \) Binary decision variable indicates whether the \( \pi \)-container could be delivered by service “l” of mode “m” on day “n”.

Output:

\( A^{(f)} \) The time of arrival at the destination node “j”.

\( TC \) The total cost for the outbound \( \pi \)-container.

Formulation

**Step 1.** Require input, including the type of the \( \pi \)-container “\( \pi \)”, its total cost “\( TC \)” up to this point and the final \( \pi \)-node “f”.

**Step 2.** Establish a list CLOSED containing only the source \( \pi \)-node and an empty list OPEN.
Step 3. For the source π-node (i=1),

\[ E^{(i)} = 0 \quad (1) \]
\[ A^{(i)} = 0 \quad (2) \]
\[ K^{(i)} = 1 \quad (3) \]

Step 4. For every π-node “i” in CLOSED, scan the outgoing links (i, j) from CLOSED and insert all “j” π-nodes into OPEN.

Step 5. For every link (i, j) between a π-node “i” in CLOSED and a π-node “j” in OPEN, select the π-node with the minimum cost. The cost of reaching each π-node is determined by the objective function described below:

Objective Function:

\[
\text{Min } Z = E^{(i)} + \left[ \sqrt{(G_p^{(f)} - G_p^{(i)})^2 + (G_A^{(f)} - G_A^{(i)})^2} \right] \cdot CK_m \\
+ \sum_{m \in \{S, A, B, R, T\}} \sum_{l \in \{1, \ldots, L_{ij}\}} \sum_{n \in \{1, \ldots, N\}} \sum_{\alpha \in \{1, \ldots, \alpha\} \cap \{1, \ldots, \alpha\}} X_{mn}^{(\pi ij)} \cdot \left[ C_{mn}^{(\pi ij)} + \left[ P \cdot TT_{mn}^{(ij)} \right] \right] \\
+ \left[ P + \Omega^{(\pi i)} \right] \cdot \left[ D_{mn}^{(i)} - A^{(i)} \right] + O_m^{(\pi j)} \quad (4)
\]

Constraints:

\[ \prod_{\alpha \in \{x, y, z\}} D_{\alpha}^{(\pi)} \leq A_{mn}^{(ij)} \quad (5) \]
\[ W^{(\pi)} \leq A_{mn}^{(ij)} \quad (6) \]
\[ D_{mn}^{(i)} \geq A^{(i)} + HT_m^{(\pi i)} \quad (7) \]
\[ X_{mn}^{(\pi ij)} \in \{0, 1\}, \quad \forall m \in \{S, A, B, R, T\}, \quad l \in \{1, \ldots, L_{ij}\}, \quad n \in \{1, \ldots, N\} \quad (8) \]
\[
\sum_{m \in \{S, A, B, R, T\}} \sum_{l \in \{1, \ldots, L_{ij}\}} \sum_{n \in \{1, \ldots, N\}} X_{mn}^{(\pi ij)} = 1, \quad \forall m \in \{S, A, B, R, T\}, \quad l \in \{1, \ldots, L_{ij}\}, \quad n \in \{1, \ldots, N\} \quad (9)
\]

Step 6. For the selected “i-j” π-node pair and the selected service number “l” of service mode “m” on day “n”:
Equation (1) initializes the artificial total cost and equation (2) initializes the arrival time. Equation (3) establishes the source $\pi$-node as the first one in the path.

In objective function (4), the first term represents the artificial total cost, up to the current $\pi$-node. The second term is a heuristic which is admissible as it cannot overestimate the cost. It estimates the cost of covering a straight-line distance between the two $\pi$-nodes by mode “m”. The third term estimates the cost of transporting the $\pi$-container between the two $\pi$-nodes. The fourth term estimates the cost caused by the artificial delivery time parameter during the transport. The fifth term estimates the cost of sojourning, including the cost caused by the artificial delivery time parameter, at the current $\pi$-node. The sixth term represents the operating cost at the next $\pi$-node.

Constraints (5) and (6) limit the capacity for additional $\pi$-containers per service. The volume and weight of the $\pi$-container to be added cannot exceed the available volume and weight capacity of service number “l” of service mode “m” on day “n”. Constraint (7) establishes that the time of departure from $\pi$-node “i” is larger (later) than the sum of the time of arrival at $\pi$-node “i” and the time node “i” needs to handle a “$\pi$” type $\pi$-container coming from mode “m”. Constraint (8) establishes $X_{\pi_{min}}^{(\pi ij)}$ as a binary variable. Constraint (9) establishes that one and only one $\pi$-container will be routed.

**Step 7.** Insert the selected “j” into CLOSED and remove it from OPEN.

**Step 8.** If $j = f$ STOP.

Otherwise go to Step 4.
Equation (10) estimates the artificial total cost for the next $\pi$-node. Equation (11) estimates the arrival at the next $\pi$-node. Equation (12) sets the next $\pi$-node as the next step of the path. Equation (13) estimates the total cost for the outbound $\pi$-container up to the next $\pi$-node.

4.5 A Distribution Protocol

A distribution protocol has to enable the last mile delivery, namely from the last $\pi$-node of the path to the final destination, completing the end-to-end delivery of the $\pi$-container. If the final destination is the last $\pi$-node, instead of a retail store, the distribution protocol described here is skipped.

The required input includes the final destination, the ETA to the last $\pi$-node, the type of the $\pi$-container and the total cost up to this point. The produced output, which is sent back to the user interface, includes the ETA to the final destination and the total cost of the end-to-end delivery.

If the last $\pi$-node is also the final destination of the outbound products, the distribution protocol described here is skipped.

The protocol is implemented through the following algorithm:

Assumptions

a) There is at least one transport service in any given day to each retail store.
b) Before a delivery is scheduled, it was been established that the final destination receive its maximum volume and weight.
c) Trucks are the only transport mode available for distribution.
d) The $\pi$-containers can be handled and opened at the final destination.
e) All the parameters are visible in an open market of transport requesters and transport providers, enabled through the open live documentation of performance and capabilities (Montreuil, 2011; Montreuil, et al., 2012).
f) All $\pi$-nodes and final destinations are constantly operational.
g) There are no unexpected delays or accidents.
Notations

Index:

- \( i, j \) Origin and destination nodes of a service.
- \( T \) Transport service executed by truck.
- \( l \) Number “l” service of different modes within a day; \( l \in \{1, ..., L_{ij}\} \). The service is defined here as a 2.4 m × 2.4 m × 12 m shipment. A single departure of a mode may include multiple services.
- \( n \) The \( n^{th} \) day of the transport. \( n \in \{1, ..., N_{ij}\} \)
- \( \alpha \) The axes of a three-dimensional Cartesian coordinate system, including (x), (y) and (z).

Input:

- \( \pi \) The type of the outbound \( \pi \)-container. The included types of \( \pi \)-containers have been described in section 4.3.
- \( TC \) The total expenditures for the outbound \( \pi \)-container.
- \( f \) The final destination.

Parameters:

- \( C_{Tln}^{(\pi ij)} \) The cost of transporting a “\( \pi \)” type \( \pi \)-container from node “i” to node “j” by truck service “l” on day “n”.
- \( P \) An artificial parameter, representing the penalty of failing to deliver timely divided by the hours from the order the agreed delivery time.
- \( \Omega^{(\pi i)} \) The cost of sojourning a “\( \pi \)” type \( \pi \)-container at node “i” per hour.
- \( D_{Tln}^{(ij)} \) The time of departure from node “i” of truck service “l” on day “n”.
- \( O_T^{(\pi ij)} \) The operating cost for a “\( \pi \)” type container arriving by truck at node “j”.
- \( AV_{Tln}^{(ij)} \) The available volume of truck service “l” on day “n” from nodes “i” to node “j”.
The maximum weight of a “π” type π-container.

The available weight of truck service “l” on day “n” from nodes “i” to node “j”.

The handling time of a “π” type π-container arriving by truck at node “i”.

The time needed for truck service “l” on day “n” to arrive to node “j” after departing from node “i”.

Variables:

The artificial total cost to reach node “j”.

The time of arrival at the destination node “j”.

Binary decision variable indicates whether the π-container could be delivered by truck service “l” on day “n”.

Output:

The time of arrival at the destination node “j”.

The total cost for the outbound π-container.

Formulation

Step 1. Require input, including the type of the π-container “π”, its total cost “TC” up to this point, the final destination “j” and the ETA to the last π-node “A(i)”.

Step 2. If \( i = j \) STOP.

Step 3. Select the optimal transport service for \( j = f \) as determined by the objective function described below:

\[
E^{(j)} = \min_Y \sum_{l \in \{1, \ldots, L\}} \sum_{n \in \{1, \ldots, N\}} X^{(\pi ij)}_{Tln} \cdot \left[ C^{(\pi ij)}_{Tln} + P \cdot TT^{(ij)}_{Tln} \right] + \left[ P + \Omega^{(\pi i)} \right] \\
\cdot \left[ D^{(i)}_{Tln} - A^{(i)} \right] + O^{(\pi j)}_T \] (1)

Constraints:

\[
\prod_{\alpha \in \{x, y, z\}} DC^{(\pi)}_\alpha \leq AV^{(ij)}_{Tln} \] (2)
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\[ W^{\pi} \leq AW^{(i)}_{Tln} \quad (3) \]

\[ D^{(i)}_{Tln} \geq A^{(i)} + HT^{(\pi\pi)}_T \quad (4) \]

\[ X^{(\pi\pi)}_{Tln} \in \{0, 1\}, \quad \forall \ l \in \{1, ..., L_{ij}\}, \quad n \in \{1, ..., N\} \quad (5) \]

\[ \sum_{l \in \{1, ..., L_{ij}\}} \sum_{n \in \{1, ..., N\}} X^{(\pi\pi)}_{Tln} = 1, \quad \forall \ l \in \{1, ..., L_{ij}\}, \quad n \in \{1, ..., N\} \quad (6) \]

**Step 4.** Update:

\[ A^{(j)} = D^{(i)}_{Tln} + TT^{(ij)}_{Tln} \quad (7) \]

\[ TC^{(k+1)} = TC^{(k)} + E^{(j)} - \left[ P \cdot TT^{(ij)}_{Tln} \right] - \left[ P \cdot \left( D^{(i)}_{Tln} - A^{(i)} \right) \right], \quad k = 0, 1, ... \quad (8) \]

In objective function (1), the first term estimates the cost of transporting the \( \pi \)-container between the last \( \pi \)-node and the final destination. The second term estimates the costs caused by the artificial delivery time parameter during the transport. The third term estimates the cost of sojourning, including the costs caused by the artificial delivery time parameter, at the current \( \pi \)-node. The fourth term represents the operating cost at the final destination.

Constraints (2) and (3) limit the capacity for additional \( \pi \)-containers per service. The volume and weight of the \( \pi \)-container to be added cannot exceed the available volume and weight capacity of truck service number “l” on day “n”. Constraint (4) establishes that the time of departure from the last \( \pi \)-node “i” is larger (later) than the sum of the time of arrival at \( \pi \)-node “i” and the time the \( \pi \)-node needs to handle a “\( \pi \)” type \( \pi \)-container arriving by truck. Constraint (5) establishes “\( X^{(\pi\pi)}_{Tln} \)” as a binary variable. Constraint (6) establishes that one and only one \( \pi \)-container will be distributed.

Equation (7) estimates the arrival at the final destination. Equation (8) estimates the total cost for the outbound \( \pi \)-container up to its final destination.
4.6 Limitations of the approach

The approach taken in this work is subject to certain limitations, largely due to its exploratory nature. The Physical Internet is a concept on its early experimental stages. As a result many of its aspects are still unclear. As we have already seen, this level of uncertainty and the lack of historic data means that many aspects of the paradigm, and consequently of the proposed reference model and protocol stack, have to be hypothesized. This problem, expected in exploratory works, paired with the limited availability of order and shipment data from the industry, effectively handicaps the possibility for the evaluation of the proposed protocol stack through simulation.

A number of assumptions have been made for each network protocol and for the reference model on which they are based, again due to the exploratory nature of the work. Some of them are based on the current or expected modus operandi of the industry, while others are simplifying the problem by removing its stochastic elements.

Arguably, the most important assumption is that the various parameters, such as the transport services, are predetermined. This is at the very core of the reference model, affecting all the proposed network protocols. There are two main reasons for making this assumption. The first one is that the reference model avoids intervening in the decision making process of both the various logistics service providers and their customers. In this way the providers are free to plan their schedules to their own best interest, while allowing their customers to plan with relative ease and certainty on a level plain field, regardless of size, market share, volume of shipments etc. The second reason is that considering the parameters as given enables the application of network optimization methods such as dynamic programming.

The assumption of known parameters, can be viable as it has been showcased by successful services such as skyscanner.com. However, in spite of its advantages, it also has limited optimizing capability. A different approach, allowing for a dynamic interaction between the service scheduling and pricing and the orders made by the user could allow for better optimization. This would be much more resource intensive, harder to operate and in need of more, potentially sensitive, information about the provider’s capabilities. Designing a reference model and a protocol stack in this way would be exponentially more complex as diverse concerns could be incorporated. To give an illustration, such an approach may have to take into account the rapid adoption
of advanced driver assistance when scheduling transport services. This in turn would need to be incorporated into the relevant framework, possibly in the form of a multiagent-based driving simulator, integrating a human factor analysis suite, as Gonçalves et al. (2014) have proposed. This would be only one of the elements of such an approach, the diversity of which would dictate the presence of an interdisciplinary design team.

Concluding this section, the reference model and the protocol stack introduced here do have limitations, however, they are relatively user friendly, lightweight and dependable while allowing considerable freedom to both the service providers and the users.
Chapter 5. Conclusion and Perspectives

This diploma thesis has attempted to provide a realistic alternative to the current logistics paradigm. Both the Physical and the Digital Internet have been explored, analyzed and subsequently compared. The ensuing analogies and contrasts between the two paradigms, and consequently the possibility for the transposition of concepts between them, have been examined thoroughly. In accordance to the results of this endeavor, a reference model has been introduced, providing a conceptual framework. An implementation of this reference model has been designed in the form of three-layered protocol stack.

This work has to be understood, however, within its exploratory context. Historically, paradigm swifts in transport and logistics internetworks have had a profound impact on economic and social development, outside the original scope of the technologies that enabled them (Bulliet, 1990). Similarly, the Physical Internet has been conceived to mitigate a number of unsustainability symptoms, but its implementation may also have ramifications that are impossible to estimate. At this stage, the objective should be to gain early insights and propose attainable implementations of the new paradigm as well as directions for further research.

In that light, this work has to be seen as a small part of a broader venture into the Physical Internet. Further research is needed and it should include simulation experiments based on real-world orders. This could produce a relatively accurate estimate of the benefits provided by the implementation of the protocol stack and enable the evaluation of each protocol. Having concrete, quantitative, results is crucial in encouraging the industry to make the transition. As the Physical Internet emerges, the various parameters will become known, drastically improving the accuracy of simulations, which in turn will provide valuable feedback. This interaction is expected to progressively become a major driving force in the topology design and operation planning of the Physical Internet. Yet, the new network architectures would presumably still be based on protocols similar to the ones proposed here.

The research opportunities are not confined, however, to simulations. Security concerns, operational and infrastructural challenges and innovative business models also constitute major avenues for further research.
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