Towards a Physical Internet:
Meeting the Global Logistics Sustainability Grand Challenge

Benoit Montreuil

Canada Research Chair in Enterprise Engineering

CIRRELT Interuniversity Research Center
on Enterprise Networks, Logistics and Transportation

Université Laval, Québec, Qc, Canada

Benoit.Montreuil@cirrelt.ulaval.ca

Abstract

This paper starts with the assertion that the way physical objects are currently transported, handled, stored, realized, supplied and used throughout the world is unsustainable economically, environmentally and socially. Evidence supporting this assertion is exposed through a set of key unsustainability symptoms. Then the paper expresses the goal to revert this situation, thus meeting the Global Logistics Sustainability grand challenge. It suggests exploiting the Digital Internet metaphor to develop a Physical Internet vision towards meeting this grand challenge. The paradigm breaking vision is introduced through a set of its key characteristics. The paper then proceeds with addressing the implications and requirements for implementing the Physical Internet vision as a means to meet the grand challenge. It concludes with a call for further research, innovation and development to really shape and assess the vision and, much more important, to give it flesh through real initiatives and projects so as to really influence in a positive way the collective future. For this to happen, it emphasizes the requirement for multidisciplinary collaboration among and between academia, industry and government across localities, countries and continents.

Keywords

Physical Internet; Global Logistics Sustainability; Grand Challenge; Logistics; Mobility; Transportation; Material Handling; Supply Chain; Supply Network; Supply Web; Open Supply Web; Greenhouse gas emission; Intralogistics; Facilities design; Containers; Modular containers; Smart containers; Packaging; Universal interconnectivity; Multimodal transport; Distributed transport; City logistics; Open distribution; Open production; Product realization; Product design; Design-for-containerization; Materializing; Dematerializing; Open performance monitoring; Capability certification; Network reliability; Network resilience; Logistics security; Business model innovation; Open logistics infrastructure

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. This unsustainability assertion, supported through numerous symptoms outlined in this paper, reveals a harsh reality. Addressing this global unsustainability is a worldwide grand challenge, hereafter termed the Global Logistics Sustainability grand challenge.

The goal of this grand challenge is to enable the global sustainability of physical object mobility (transportation, handling), storage, realization (production, assembly, finishing, refurbishing and recycling), supply and usage. From an economical perspective, the goal is to unlock highly significant gains in global logistics, production, transportation and business productivity. From an environmental perspective, 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 transportation. From a societal perspective, the goal is to significantly increase the quality of life of the logistic, production and transportation workers, as well as of the overall population by making much more accessible across the world the objects and functionality they need and value.

The global logistics sustainability grand challenge cannot be addressed through the same lenses that have created the situation. The current logistics paradigm must be replaced by a new paradigm enabling outside-the-box meta-systemic creative thinking.

Decades ago, the information and telecommunications community similarly faced a grand challenge. Drastically summarized, the digital world had faced a fast evolution from a world dominated by isolated large computers to a world filled with minicomputers and their workstations linked by private networks, and then to an explosive world filled with unconnected microcomputers sitting on everyone’s desk. Most authorities in the community agreed that the situation was unsustainable and macroscopic solutions were needed. As the digital world was looking for a way to conceptualize how it should transform itself, it relied on a physically inspired transportation and logistics metaphor: building the information highway.

As is well known today, the digital community achieved its goal and went farther, reshaping completely the way digital computing and communication are now performed. The Digital Internet was invented, notably leading the way to the digital worldwide web and digital mobility. The reconceptualization has enabled the building of an open distributed network infrastructure that is currently revolutionizing so many facets of societal and economic reality. At the core of the paradigm shift is the Digital Internet which is about the interconnection between networks in a way transparent to the user, so allowing the transmission of formatted data packets in a standard way permitting them to transit through heterogeneous equipment respecting the TCP/IP protocol [1,2].

As the digital world exploited a physical world inspired metaphor, it is proposed that in order to meet the current grand challenge, the physical world exploit a digital Internet inspired metaphor. Even though there are fundamental differences between the physical world and the digital world, the metaphor is to be exploited to propose a vision for a sustainable and progressively deployable breakthrough solution to the global problems associated with the way physical objects are transported, handled, stored, realized, supplied and used around the world. The vision that will be presented in the paper is to evolve towards a Physical Internet as a solution to the global logistics sustainability grand challenge.

The remainder of the paper is structured as follows. Section two provides evidence supporting the global logistics unsustainability assertion. Section three describes the Physical Internet vision through its key characteristics. Section four addresses the implementation of the vision. Final section five provides conclusive remarks and outlines avenues for further research.

2. Supporting the global logistics unsustainability assertion

From an economical perspective, the way goods are flowed is hugely costly. In most developed countries, it accounts for a significant fraction of the gross national product. The U.S.A. provides a vivid example. Based on statistics from the 2009 Department of Transportation reports [3], transportation represents about 10% of the U.S. Gross Domestic Product, or roughly \$1.4T (trillion). Expenditures on freight transportation, packaging and commercial warehousing are \$500B (billion), \$125B and \$33B, respectively, excluding all costs directly incurred by manufacturers, distributors and retailers [4]. Thus, for the U.S.A., the annual stakes are easily in the billions of dollars.

From an environmental perspective, the stakes are also high. Again, the U.S.A. provides a vivid example [3]. In 2006, road-based transportation had 8.8 million trucks traveling 263 billion miles a year. Overall, freight generates 3.7T ton-miles of transportation through air-truck-rail-water modes. In 2007, the combination of truck and train freight transportation modes consumed 42 billion gallons of fuel. This is an enormous consumption of energy and source of both pollution and greenhouse gas emissions. France is another typical example [5]. Freight flow travel has had and is forecast to have a fast growth, on the order of 37% of tons-kilometers from 2005 to 2025. Freight transportation generates 14% of the greenhouse gas emissions in France, having grown by an annual rate of +23% from 1990 to 2006 while the country's objective is a major reduction of 20% targeted by 2020, and of 75% by 2050.

Beyond such big-picture numbers, the societal, environmental and economical unsustainability of logistics across the planet can be grasped through numerous symptoms. Below are reported thirteen such vivid symptoms.

1. *We are shipping air and packaging*

Trucks, wagons and containers are often half empty at departure, with a large portion of the non-emptiness being filled by packaging [6]. As an example, official statistics report that in the U.S.A. trailers are approximately 60% full when traveling loaded [7,8]. Overall, the global transport efficacy has recently been estimated to be lower than 10% [9].

2. *Empty travel is the norm rather than the exception*

Vehicles and containers often return empty, or incur extra travel routes to find return shipments. Furthermore vehicles leaving loaded get emptier and emptier as their route unfolds from delivery point to delivery point. In the UK, the proportion of truck-kilometers travelled empty was reported in 2004 to be on the order of 27% [10]. In 2009, the U.S.A. industry average was that 20% of all miles are driven with a completely empty trailer [9], with many more nearly empty.

3. *Truckers have become the modern cowboys*

Road based transportation dominates continental transport means. This means a high demand for truck drivers. For example, the America Trucking Association has estimated that the driver shortage in the U.S.A. will grow to 111,000 by 2014 [11]. Yet, the current way of doing is such that so many truckers are nearly always on the road, so often away from home for long durations. Their family life, their social life and their personal health are precarious. As an illustrative indication, a U.S. National Transportation Safety Board study found that 58% of the accidents reported by drivers were deemed to be fatigue and sleep deprivation related [12].

4. *Products mostly sit idle, stored where unneeded, yet so often unavailable fast where needed*

Manufacturers, distributors, retailers and users are all storing products, often in vast quantities through their networks of warehouses and distribution centers, yet service levels and response times to local users are constraining and unreliable. As an indication of the size of inventory, the average investment in all U.S. business inventories was $101B in 2005 [11].

5. *Production and storage facilities are poorly used*

Most businesses invest in storage and/or production facilities which are lowly used most of the times or for significant parts of the year, or yet badly used, dealing with products which would better be dealt with elsewhere, forcing a lot of unnecessary travel. For example, warehouses are under-utilized for large portions of the year due to the seasonal nature of most products, while these same facilities are over-taxed during their peak, leading to inefficient, short-term practices to meet peak demand.

6. *So many products are never sold, never used*

A significant portion of consumer products that are made never reach the right market on time, ending up unsold and unused at some location, while they would have been required elsewhere. Even though hard statistics are rare on this sensitive issue, this is well known in the food and clothing industries, and also happens with high-price products such as cars, anecdotally evidenced by rusting new cars in a disused airfield.

7. *Products do not reach those who need them the most*

As one gets away from the core of the developed countries and into less developed countries, the transportation and logistics infrastructures, capabilities and service levels decrease very significantly, making it difficult, costly and lengthy to reach those in need in such countries. The same occurs in crisis and disaster zones where the established infrastructure gets totally or partially destroyed due to the lack of resilience and of fast adaptability capability of current infrastructures and networks. The impact is disastrous when both less-developed and disaster conditions occur concurrently.

8. Fast and reliable intermodal transport is still a dream or a joke

Even though there are some great intermodal examples [13], notably associated with cargo container transport and logistics, in general synchronization is so poor, interfaces so badly designed, that intermodal routes are mostly time and cost inefficient and risky. This is exacerbated by the fact that the least energy efficient transportation modes are more used. For example, trucks are much more used than trains while the former emit twenty times more CO_2 than the latter.

9. Getting products in, through and out of cities is a nightmare

Most cities are not designed and equipped for easing freight transportation, handling and storage. This makes the feeding of businesses and users in cities a nightmare, while creating significant traffic, noise and pollution concerns for citizens. This gets more acute as cities are more populated and older. Even though there are several city logistics and urban mobility initiatives [14], results are still modest.

10. Products unnecessarily move, crisscrossing the world

Products commonly travel thousands of kilometers that could have been avoided by routing them smartly and/or making them much nearer to their point of use. The outsourcing of product manufacturing to developing countries has accentuated this phenomenon. Yet, even without it, such factors as the hub-and-spoke networks and the centralization phenomenon leading to one or a few large of distribution centers covering wide geographical areas, lead to excessive travel.

11. Networks are neither secure nor robust

There is extreme concentration of operations in a limited number of centralized production and distribution facilities, with travel along a narrow set of high-traffic routes. This makes the logistic networks and supply chains of so many businesses, unsecure in face of robbery and terrorism acts, and not robust in face of natural disasters and demand crises. Supply chain and logistic network vulnerability, risk and resilience are ever more critical issues [15, 16].

12. Smart automation and technology are hard to justify

Vehicles, handling systems and operational facilities have to deal with so many types of materials, shapes and unit loads, with each player independently and locally deciding on his piece of the puzzle. The historical France-Spain train example where both countries made sure that rail width differ in the two countries so that trains from the other country could not move along their country's rail system still applies today to so many facets of material handling, storage and transport technology. This makes it very hard to justify smart connective technologies (e.g. RFID and GPS), systemic handling and transport automation, as well as smart collaborative piloting software [e.g. 17].

13. Innovation is strangled

Innovation is bottlenecked, notably by lack of generic standards and protocols, transparency, modularity and systemic open infrastructure. This makes breakthrough innovation so tough, justifying a focus on marginal epsilon innovation. Conveyors, fork lifts and storage systems are just a few examples suffering from this innovation strangling, resulting in a limited number of breakthrough innovations in recent decades.

Table 1 relates the thirteen symptoms to economical, environmental and societal sustainability issues. All symptoms have significant negative economical impact and have either a negative environmental or societal impact, or yet have three-faceted negative impact. Overall the thirteen symptoms combine to create an impressionist picture of the current unsustainability reality and of the important need for change to avoid hitting the wall.

Table 1. The unsustainability symptoms

	Unsustainability symptoms	**Economical**	**Environmental**	**Societal**
1	**We are shipping air and packaging**	●	●	
2	**Empty travel is the norm rather than the exception**	●	●	
3	**Truckers have become the modern cowboys**	●		●
4	**Products mostly sit idle, stored where unneeded, yet so often unavailable fast where needed**	●		●
5	**Production and storage facilities are poorly used**	●	●	
6	**So many products are never sold, never used**	●	●	●
7	**Products do not reach those who need them the most**	●		●
8	**Products unnecessarily move, crisscrossing the world**	●	●	
9	**Fast & reliable intermodal transport is still a dream or a joke**	●	●	●
10	**Getting products in and out of cities is a nightmare**	●	●	●
11	**Networks are neither secure nor robust**	●		●
12	**Smart automation & technology are hard to justify**	●		●
13	**Innovation is strangled**	●	●	●

3. The Physical Internet vision

In June 2006, the front page of The Economist [18] had a big headline introducing the term 'Physical Internet'. The issue presented a survey of logistics, with interesting high-quality yet mainstream supply chain and logistics articles. Beyond the headline, there was no other mention of the term Physical Internet. This rose the author's research interest and curiosity. What should or could be a full-blown Physical Internet? How would it compare and contrast with the Digital Internet? What would be its key features? What capabilities would it offer that are not achievable today? Another question surfaced rapidly: Why would the world need a Physical Internet?

The answer to this latter question lead to the realization that the current way physical objects are transported, handled, stored, supplied, realized and used is not anymore sustainable, as depicted through the symptoms outlined above. The other questions lead to define the Physical Internet vision through the thirteen characteristics described hereafter.

1. *Encapsulate merchandises in world-standard smart green modular containers*

The Digital Internet does not transmit information: it transmits packets embedding information. These packets are designed for ease of use in the Digital Internet. The information within a packet is encapsulated and is not dealt with by Internet. The packet header contains all information required for identifying the packet and routing it correct to destination. A packet is constructed for a specific transmission and it is dismantled once it has reached its destination. The Digital Internet is based on a protocol structuring data packets independently from equipment. In this way, data packets can be processed by different systems and through various networks: modems, copper wires, fiber optic wires, routers, etc.; local area networks, wide area networks, etc.; Intranets, Extranets, Virtual Private Networks, etc. [19, 20]

It should not be surprising that some of the currently most efficient logistics systems are associated, on the large side, with world standard 20 and 40 feet container transport, handling and storage [6], and on the small side, with parcel logistics as deployed by giants such as DHL, FedEx, Purolator and UPS. Both types are exploiting standardization of physical packets in the form of containers and parcels respectively. The Physical Internet generalizes and significantly extends this praxis.

The Physical Internet encapsulates physical objects in physical packets or containers, hereafter termed π-containers so as to differentiate them from current containers. These π-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 π-containers are [21]:

- 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.

In order to illustrate the modularity of external dimensions of π-containers and to steer discussions, consider as a potential set of dimensions along the X, Y and Z axes the following measures: 0,12 m, 0,24 m, 0,36 m, 0,48 m, 0,6 m, 1,2 m, 2,4 m, 3,6 m, 4,8 m, 6 m and 12 m. The set of exact modular dimension measures is to be subject to an international standards committee so as to gather maximal consensus. Figure 1, sourced from [21], depicts the modularity of π-containers by illustrating how composite π-containers can be composed from unitary π-containers, and later decomposed into sets of unitary and smaller composite π-containers.

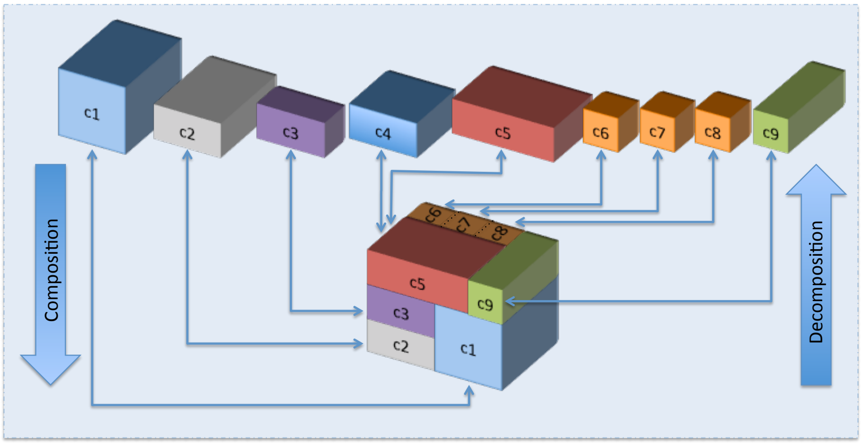

Figure 1. Illustrating the modularity of unitary and composite π-containers

The π-containers are key elements enabling the interoperability necessary for the adequate functioning of the Physical Internet.

2. *Aiming toward 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 crossdocking 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. As the Physical Internet has to operate as well in Chicago as in Dakar, between the Netherlands and Italy as well as between Helsinki and Beijing, or yet as well from Singapore to Los Angeles as from Québec to Iqualuit, this universal interconnectivity between automatic, automated, mechanically assisted and manual operations is of upmost necessity.

A key objective of the universal interconnectivity through the Physical Internet is to make load breaking almost negligible temporally and economically. For example, a target is for intermodal less-than-truckload transport to be nearly at the same price, speed and reliability as current single-mode full truckload.

3. *Evolve from material to π-container handling and storage systems*

In the Physical Internet, there are no generic all-purpose material handling and storage systems. There are only π-container material handling and storage systems embedding innovative technologies and processes exploiting the characteristics of π-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 [21].

The π-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 π-containers;
- Monitoring and protecting the integrity of π-containers;
- Securing the π-containers 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 operations.

As introduced in [21], the π-nodes of the Physical Internet are composed of sites, facilities and systems such as:

- π-transit: transferring π-carriers (carrying π-containers) from their inbound π-vehicles to their outbound π-vehicles;

- π-switch: transferring uni-modally π-containers from an incoming π-mover to a departing π-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 journey across the Physical Internet;
- π-hub: transferring 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 [21], they are in general more streamlined and standardized than their current counterparts.

4. *Exploit smart networked containers embedding smart objects*

The Physical Internet exploits as best as possible the capabilities of smart π-containers connected to the Digital Internet and the World Wide Web, and of their embedded smart objects, 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 similar to the MAC access in the Digital Internet [22] 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 [21]. The smart tag exploits technologies such as RFID and GPS [23, 24, 25]. As true with all other elements of the Physical Internet, the implementation of smart tags will evolve with technological innovations.

Smart tags are an element of the Internet of Things [26], which is about enabling ubiquitous connection with physical objects equipped with smart connective technologies, making the objects ever smarter and enabling distributed self-control of objects through networks. The Physical Internet is to exploit as best as possible the Internet of Things to enable the ubiquitous connectivity of its π-containers and π-systems.

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

In the Digital Internet, the data packets that constitute an overall transmission, such as an email, do not travel directly from source node A to destination node B. The packets travel through a series of routers and cables (copper or optical), dynamically moved from origin to destination in as best a way as possible provided the routing algorithms and the congestion through the networks. For example, an email from Québec to Lausanne may go through tens of routers across the world. Packets forming a message are not restricted to travel together. Each may end up traveling its distinct route, then the overall message is reconstituted upon the arrival of packets at final destination [1].

Current logistics is 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.

A simple example can illustrate the difference. A shipper wants to have a trailer fully loaded with containers transported from Québec to Los Angeles. According to the current way, there is high probability that (1) a driver and a truck will be assigned to the multi-day trip, (2) the driver will drive all the way to destination, sleeping in the truck, and (3) once having delivered the trailer in Los Angeles the driver will move the truck to some as nearby as possible location to pick up a trailer returning toward as near as possible of Québec so as to avoid empty travel.

In the Physical Internet, such a point-to-point experience would be exceptional. Most probably, the scenario would unfold as follows. A first driver-truck duo would be assigned to transport the trailer to a transit two to six hours away. The trailer would then be deposited to a slot in a π-transit or π-hub. The first duo would then pick up another trailer required toward Québec. A second driver-truck duo would soon afterward pick up the trailer 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 containers have reached Los Angeles. The shipper or its representative would have a priori arranged transportation on each segment and sojourn at each π-transit or π-hub, in his 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.

Figure 2 contrasts the current way with the Physical Internet way, assuming simple distributed truck based transport in the Physical Internet way. In the current way, the single driver would travel over 10,000 km round trip for a duration of at least 240 hours, with the containers reaching Los Angeles after 120 hours. In the distributed way, seventeen drivers would each drive in average about six hours, each thus returning home with his truck in a single day, yet collectively getting the containers in Los Angeles in roughly 60 hours, about half the current time.

	Current	Proposed
Distance travelled one-way:	5030 km	5030 km
Drivers:	1	17
Trucks:	1	17
Trailer:	1	1
One-way driving time (h):	48	51+
Return driving time (h):	48+	51+
Total time at transit points (h):	0	9
Total trailer trip time from Quebec to LA (h):	120	60+
Total trailer trip time from LA to Quebec (h):	120+	60+
Total trailer round trip time (h):	240+	120+
Average driving time per driver (h):	96+	6
Average trip time per driver (h):	240+	6,5

Figure 2. Contrasting current point-to-point transport
and Physical Internet enabled distributed transport

In general, the shift is towards distributed multi-segment travel of π-containers through the Physical Internet with:

- Distinct carriers and/or modes taking charge of inter-node segments;
- Hubs and transit nodes enabling synchronized transfer of π-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. Here two key differences with the Digital Internet are at stakes. First, every single move or sojourn of a π-container, and every single physical operation on it, is costly, even though as little as possible. Second, there is no apparent instantaneity: every move and operation takes time. A physical trip from Québec to Los Angeles will always take significant time until object-beaming technology moves from science fiction to practical reality. This time significance allows planning in the Physical Internet by orders of magnitude more researched and optimized than in the Digital Internet. Indeed when a freight train departs from Paris to Berlin, there are numerous hours to plan what to do upon its arrival at the Berlin hub, time that is not available for a data packet with the same origin and destination that is expected to be arrived before one has even begun to think how it is to get from origin to destination.

Ultimately, shippers would just state to their π-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 π-containers would decide on their routing dynamically, adapting their plans in route. They would call back to the shipper or his representative human or virtual logistic agent 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 π-container, which simply relays information to an agent that takes the decisions in its place, and transmits it to both the π-container and, when appropriate, the Physical Internet elements involved in the route. The agent either takes the routing decisions on a one-by-one basis or considers a number of π-containers under his/its control. The π-containers and local π-elements only take initiative in cases of agent unavailability or incapability to respond in time to urgent decisional need.

In another option nearer to current ways of doing, 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. For example, in the Québec-to-Los-Angeles example of Figure 2, they could have impose that (1) the containers be routed to a Chicago-based truck-train hub and (2) they be using the train from Chicago to Kansas City.

All these options rely on the logistic providers exploiting the nodes, links and movers to rapidly and reliably provide users, their agents or their π-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 huge difference between having to ship once a set of π-containers from Québec to Los Angeles and having to do so every single day of the year for at least three years. 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. This can be expressed in a Russian-dolls style multi-level way, with networks being 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;
7. Worldwide inter-continental networks.

As an example, at the fourth level, the Physical Internet is to structure inter-city travel with π-transits and π-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.

Figure 3 provides an example of two interconnected intra-state inter-city networks, one in the Québec province of Canada coupled to another in the northeastern states of the U.S.A. It shows the Canadian links and nodes in red, and the American ones in blue. It notably exhibits dual π-nodes at the borders, allowing π-containers to be efficiently and securely passed between the countries without requiring vehicles to cross the borders.

Similarly, at level three, the Physical Internet can allow to structure and to empower sustainable city logistics networks, helping to efficiently getting products into, through and out of cities while minimizing negative impacts on citizens' quality of life related to freight logistics such as pollution, noise, traffic and safety issues.

Figure 4 uses the Québec City metropolitan region for illustration purposes. It depicts the envelope of its intra-city network as it could be implemented in the Physical Internet. It shows π-hubs and π-transits located at key locations near the highways around the city region. In this example, all incoming and outgoing freight would have to go through one of the surrounding π-nodes. Travel within the city region would be limited to π-containers transported by green π-movers according to an intra-city network infrastructure.

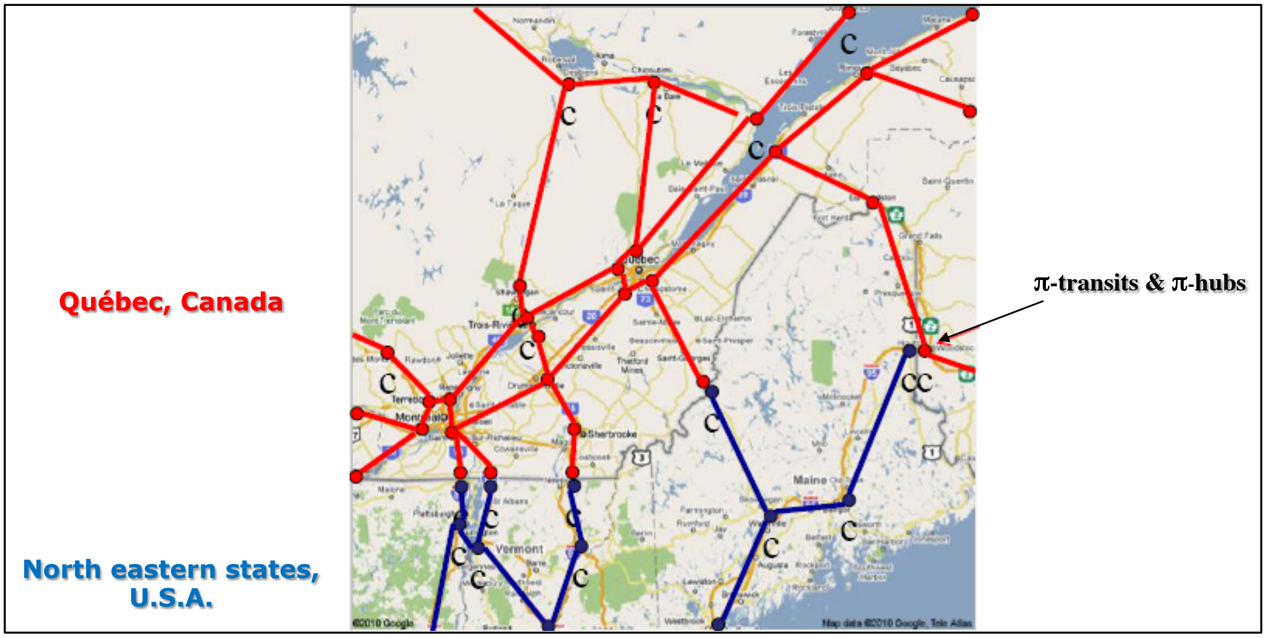

Figure 3. Illustrating an inter-city network covering
the south of the province of Québec in Canada and the northeastern states of the U.S.A.

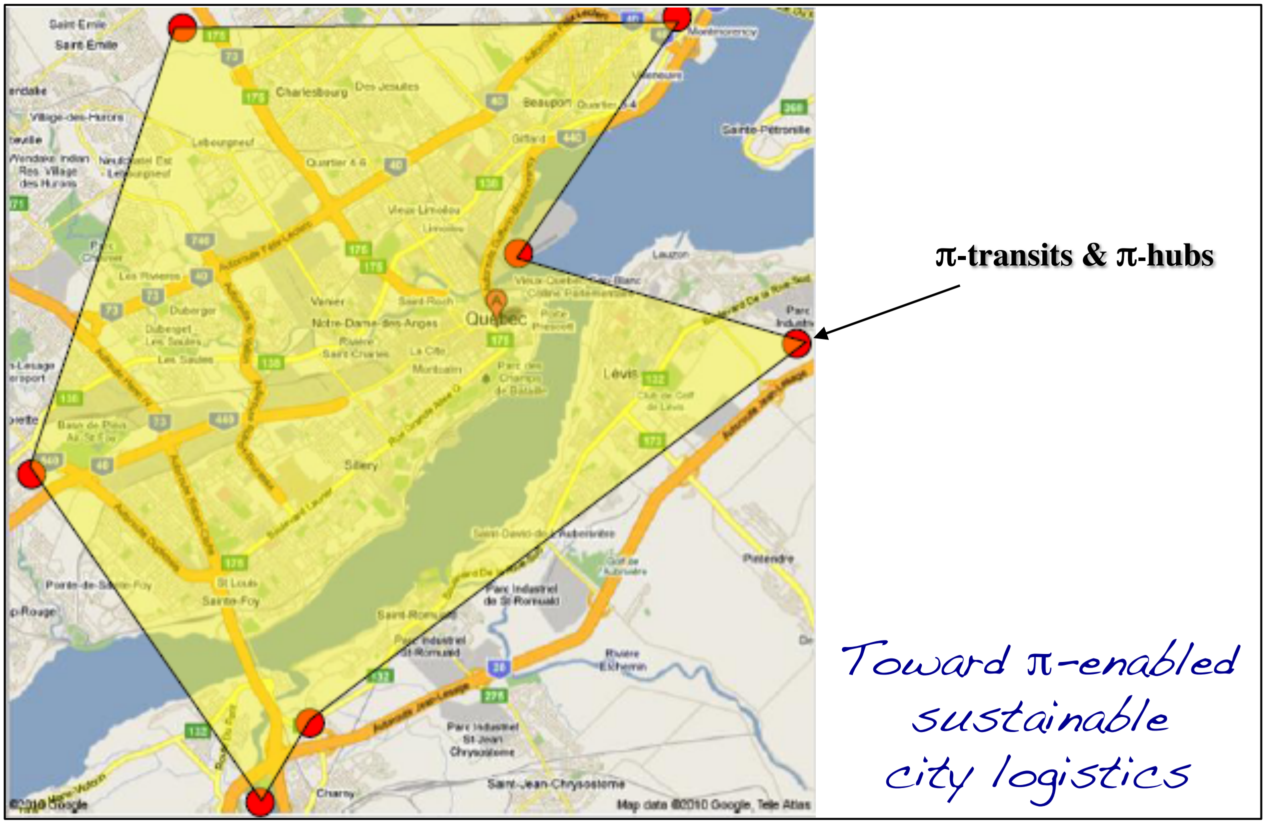

Figure 4. Illustrating the envelope of Québec's intra-city inter-site network

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 [27, 28]. 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 at most ten 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 π-containers allows warehouses and distribution centers to accept handling and storing π-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. Just in the U.S.A. there are currently about 535,000 warehouses and distribution centers. This means that ultimately in that country the Physical Internet allows each enterprise to dynamically deploy its π-container embedded products across an open web of 535,000 logistic facilities.

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 π-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 huge potential positive consequences for enterprises, in terms of supply productivity, responsiveness, adaptability and resilience, to name a few criteria.

Figure 5 uses a simple matrix world to contrast the concepts of private supply networks, shared supply webs and open supply webs. Each cell in the matrix corresponds to a region. Travel induced lead time between regions corresponds to the rectilinear distance between their centroids, with a one-day lead time between adjacent regions. Clients in each region expect a maximum three-day inter-region-transport induced lead time from their suppliers.

The upper part of Figure 5 depicts the cases of four such suppliers, each having a single factory at a fixed location and aiming to serve all regions. The four suppliers independently optimized their network given their factory location, implementing distribution centers (DCs) at optimized locations to satisfy the three-day delivery constraint. Their factory also acts as a distribution center. The leftmost firm has implemented four DCs, resulting in an average DC-to-client lead time of 1,73 day. The other three suppliers have done similarly. Globally, they have independently implemented 16 DCs, resulting in an average DC-to-client lead time of 1,75 day. Feeding the DCs from their factory involves an average lead time of roughly four days which has to be covered by safety stocks at their DCs in order to avoid shortages causing disruption of delivery service to clients.

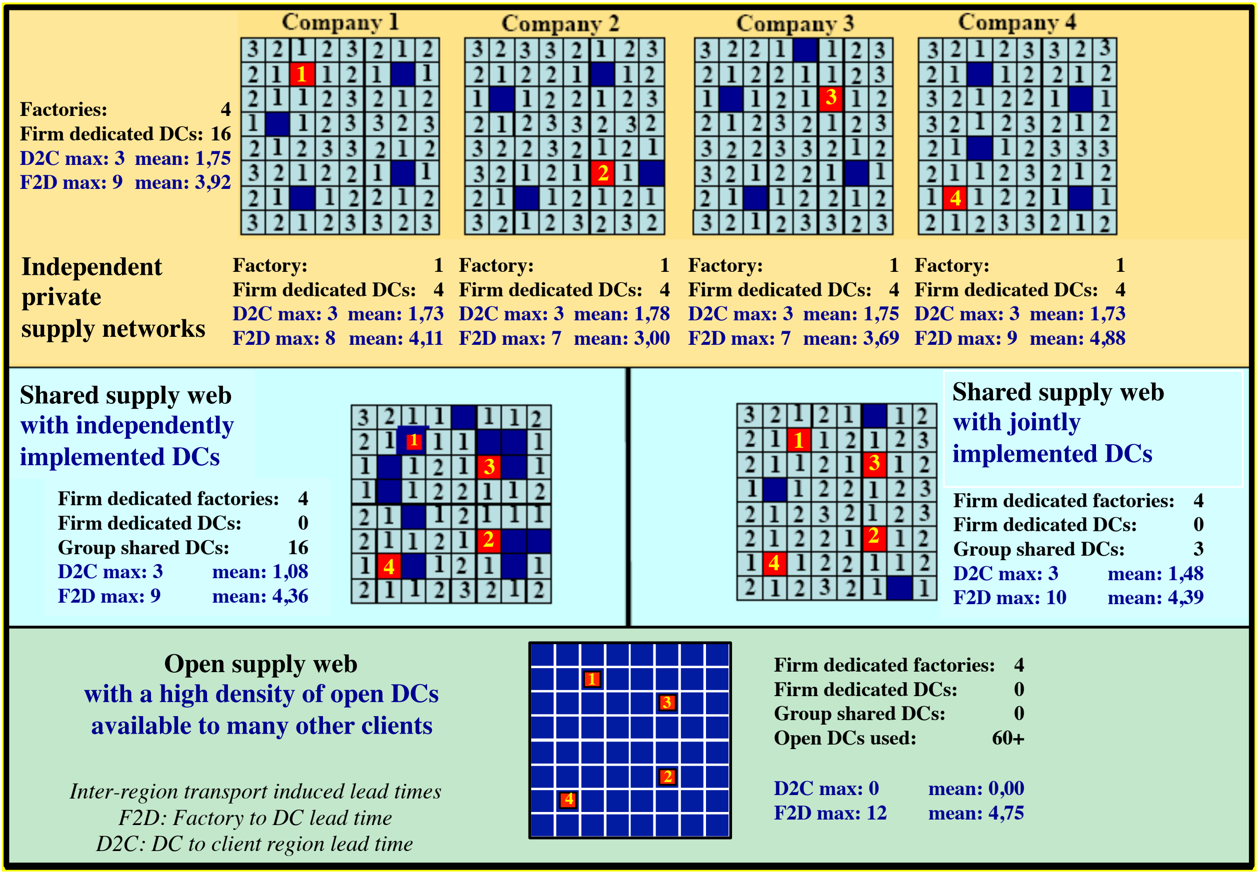

Figure 5. Contrasting private supply networks, shared supply webs, and open supply webs, assuming webbed sharing and openness in distribution, but not in production

The middle portion of Figure 5 depicts cases where the four suppliers enter a partnership enabling them to jointly exploit a shared supply web. In the left case, the 16 DCs that were originally implemented and exploited independently are now made available to all four suppliers. This results in the average lead time shifting from 1,75 to 1,08 day with the same twenty facilities. In the right case, the four suppliers jointly optimize their DCs so as to minimize the overall number of DCs required. It results in a huge reduction of the number of facilities from 20 to 7, with three DCs and four distribution-capable factories, delivering clients within an average lead time of 1,48 day. In both cases, this involves a slight increase in factory-to-DC lead time of less than half a day in average.

The lower portion of Figure 5 depicts the case where the four suppliers are part of an open supply web spanning the entire matrix world. The four suppliers are far from being the only ones serving clients in regions of this world. In fact, there are open DCs spread all over the matrix world. This leads to a fundamental shift. The suppliers do not even have to implement new DCs, except if there would be overall capacity shortage within the entire supply web. Assuming this is not the case, each supplier exploits DCs in every region, even more than one per region, as it deems necessary, dynamically deploying its stock according to demand fluctuations. In this case, the minimum number of used open DCs is 60, yet the real number can climb to 240 if each supplier picks a distinct DC in each region, and to higher numbers as they dynamically spread their stock through multiple DCs per region. From a delivery lead time perspective, the shift toward an open supply web enables the inter-region travel induced lead time to ultimately fall down to zero as suppliers move to deploy their stock in open DCs within each region. This shift causes only an increase of about three fourth of a day over the independent private supply network case, mostly due to the fact that there are now DCs exploited in all corners of the matrix world.

This simple example can be transposed from the matrix world to the real world, in each and all of the continents. Figure 6 provides an example applying its logic to firms deserving targeted city markets across Canada and the U.S.A.

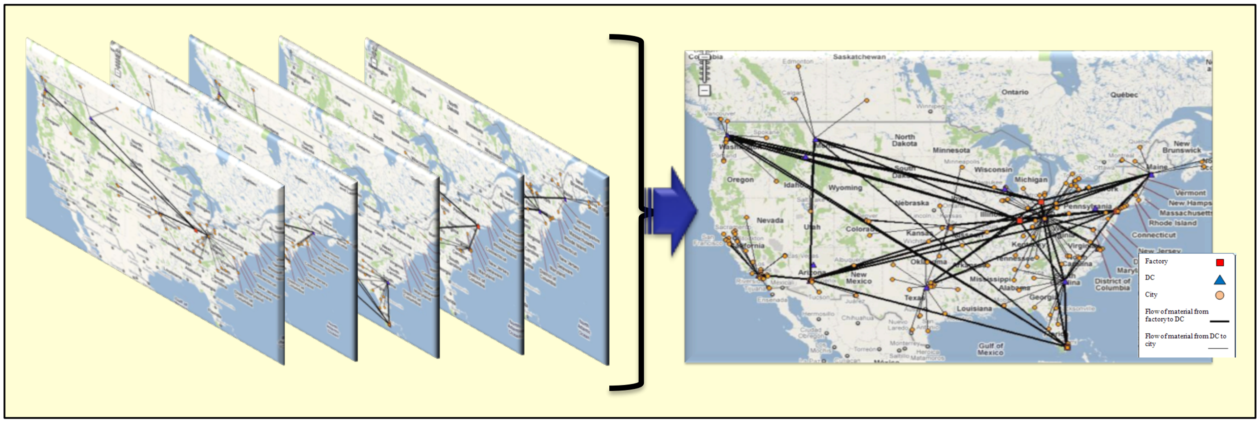

Figure 6. From private supply networks to an open supply web: an illustration with five firms serving targeted markets in North America

8. *Design products fitting containers with minimal space waste*

The Physical Internet embeds physical objects (freight, merchandises, products, materials) within modular π-containers. Thus, the objects to be carried within π-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 π-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 π-container as small as possible so as to avoid moving and storing air within the π-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 much easier and faster, and much less expensive, 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.

In order to illustrate the potential impact of distributed production through local materialization and outsourcing, Figure 7 revisits the matrix world case of Figure 5. In contrast with Figure 5, it depicts cases where production is not limited for each firm to its dedicated factory. The cases in the upper and middle portions of Figure 7 correspond directly to their counterparts in the middle and lower portions of Figure 5. In the shared supply web cases, the four firms are now sharing their factories, without altering the overall number of facilities. The top left case shows that the webbed sharing allows reducing by a ratio of four to one the mean lead time for feeding the sixteen independently implemented shared DCs, passing from 4,4 to 1,1 days. The top right case shows a larger reduction from 4,4 to 0,8 days. These imply a much higher responsiveness for the DCs, having to support much less stock to avoid shortage. Adding both the DC-to client and factory-to-DC lead times reveals that the best achieved is (1,48+0,83)=2,31 days.

The middle and lower parts of Figure 7 address the open supply web case that exploits a high density of open DCs available in each region of the matrix world. The middle portion allows production to be shared among the four suppliers. This reduces the mean total lead time from 4,75 to 2 days, a significant improvement over the best 2,66 days obtained with a shared supply web. Yet the real gain comes when the firms are allowed to also exploit a high density of open production centers spread across the regions, leading both the inter-region transport induced DC-to-client and Factory-to-DC lead times to be zero, and enabling not having to always rely on DCs, exploiting just-in-time production and delivery to clients whenever applicable.

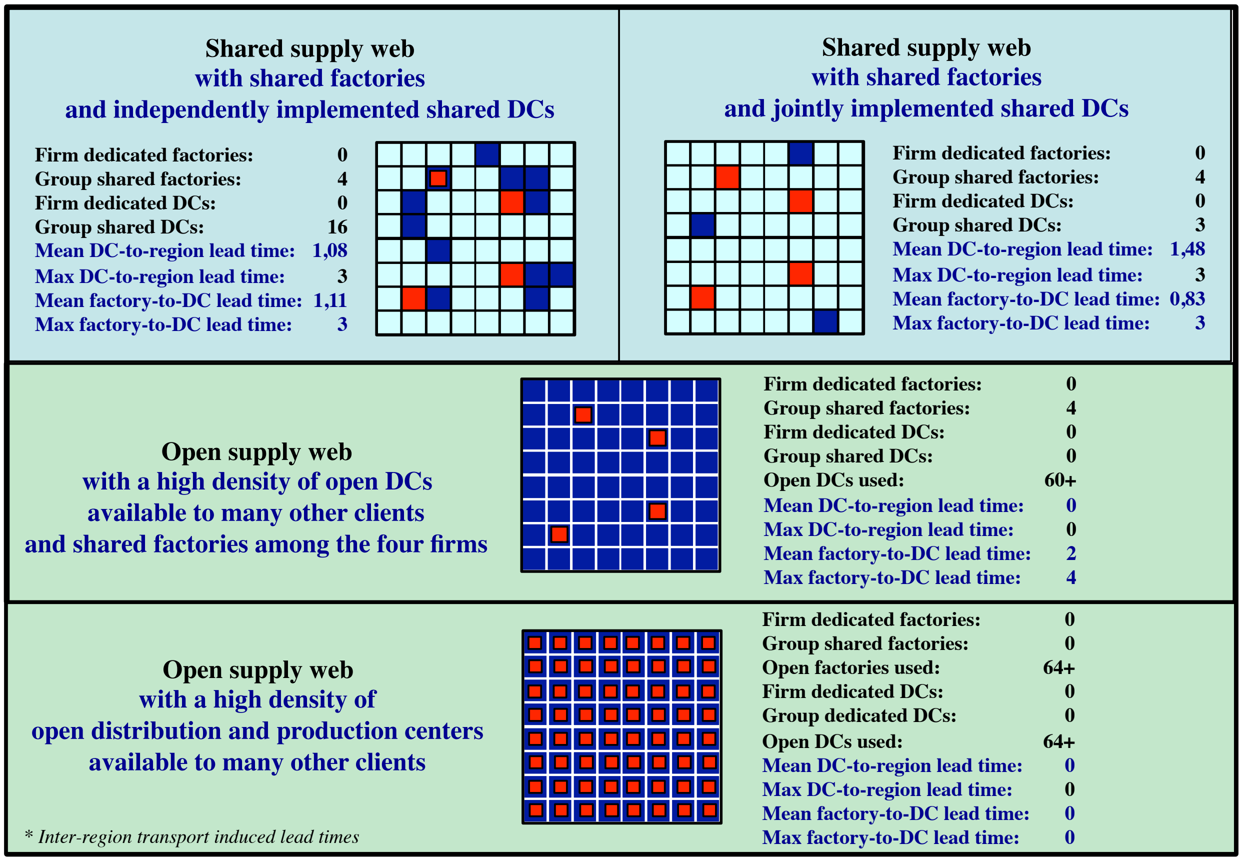

Figure 7. Contrasting private supply networks, shared supply webs, and open supply webs, assuming webbed sharing and openness in distribution and production

This is clearly an ultimate example, yet Figures 5 and 7 demonstrate that there is a huge potential performance to be gained 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 really achieved 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.

For example, a Physical Internet port would post openly on the Digital Web its live and historical performance in terms of:

- Ship unloading and loading times;
- The time between the moment a ship enters the port and the moment its unloaded containers are available to be shipped by land;
- Container sojourn times in the port;
- Lead times to get access to the port by a ship and by land (truck or train);
- And so on.

Such live performance tracking is openly available worldwide 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, as the Digital Internet relies heavily on certifications of its protocols and its numerous entities, 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 centers, roads, protocols, processes, and so on.

A π-certified container would meet all functional specifications for such containers (refer to section 1), 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 within, for example, an average of 125 minutes with a maximum of 150 minutes 99,9% of the times.

At higher scales, cities and regions could be π-certified, subject to strict capability measures insuring that, within their boundaries, freight is dealt by π-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, and will be attracted to improve their certification levels.

11. *Prioritize webbed reliability and resilience of networks*

The Digital Internet aims to transport information flows in a reliable and resilient manner by its intrinsic nature, its protocols and its structure. It not only transmits information from any one point to any other point within the networks, it also works at insuring its coherence and avoiding its corruption by external elements, notably through its data encapsulation in packets.

Similarly, the overall Physical Internet 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 [15] to unforeseen events. For example, if a node or part of a network fails, the traffic of π-containers should be easily re-routable as automatically as possible.

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 π-containers;
- The physical and informational integrity of π-containers, π-movers, π-routes and π-nodes;
- The informational integrity of π-actors such as humans and software agents;
- The robustness of client-focused performance in delivering and storing π-containers.

12. *Stimulate business model innovation*

Essential in the Physical Internet vision is a worldwide set of actors with innovative business models [29,30] commercializing novel offers enabled by and adapted to the Physical Internet, with innovative revenue models for the various stakeholders.

The Digital Internet has created a plethora of new businesses and business models, from service providers, to platform builders and e-retailers. The advent of the Physical Internet has the potential to have a similar impact, stimulating business model innovation all across industry.

This business model innovation is to occur in the various logistics and transport industries. How are to evolve the material handling and transportation solution and technology providers, the freight transporters and the logistics providers, so as to best thrive from the emerging Physical Internet? How are to evolve the various software providers, from execution systems to strategic logistics network and supply chain design systems?

In the retailing, service, distribution and manufacturing industries, there is also bound to have business model innovation. How are to evolve the manufacturers, distributors, retailers so as to best exploit the Physical Internet and its Global Open Supply Web?

Overall, what will be the new types of business models dominating a Physical Internet enabled industry? What are to be the Physical Internet enabled equivalents of Digital Internet enabled Amazon, eBay and Google that have reshaped the global business landscape?

13. *Enable open infrastructural innovation*

The systemic coherence and universal interconnectivity of the Physical Internet are to enable the transparent usage of heavy handling, storage and transport means currently existing or to come in the future, that are now so hard to use, currently limiting their potential positive environmental impact.

The Physical Internet homogeneity in terms of modular π-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.

As an example of the potential open infrastructural innovation that could be enabled by the Physical Internet, consider a network of intercity very-high-speed π-container trains or subways. In the eastern U.S.A., imagine linking Boston and New York with a green-energy low-noise very-high-speed container subway/train. Today, even if it would be technically feasible to build such a link, its logistics performance would be deterred at its two extremities, getting freight to the link and getting it out once having reached the other city. The Physical Internet eases the technical design and engineering of the entire infrastructure, including the vehicles and carriers, the hubs and the connections with the logistics networks at both extremities. The huge freight flow between such cities could make such an efficient infrastructure economically, environmentally and socially feasible and attractive.

Table 2. Physical Internet addressing unsustainability symptoms

		Physical Internet Characteristics												
		1	2	3	4	5	6	7	8	9	10	11	12	13
	Unsustainability symptoms	Objects encapsulated in world standard modular containers	Universal interconnectivity	Container handling and storage systems	Smart networked containers embedding smart objects	Distributed multi-segment intermodal transport	Unified multi-tier conceptual framework	Open global supply web	Product design for containerization	Product materialization near to point of use	Open performance monitoring and capability certification	Webbed reliability and resilience of networks	Business model innovation	Open infrastructural innovation
1	**We are shipping air and packaging**	●							●					
2	**Empty travel is the norm rather than the exception**		●			●								
3	**Truckers have become the modern cowboys**			●		●								
4	**Products mostly sit idle, stored where unneeded, yet so often unavailable fast where needed**	●			●			●						
5	**Production and storage facilities are poorly used**	●	●	●				●	●	●				
6	**So many products are never sold, never used**							●		●		●	●	
7	**Products do not reach those who need them the most**		●			●	●	●		●		●		
8	**Products unnecessarily move, crisscrossing the world**		●		●	●					●			●
9	**Fast & reliable intermodal transport is still a dream or a joke**	●	●	●	●	●	●				●			●
10	**Getting products in and out of cities is a nightmare**	●	●		●	●	●	●		●		●		
11	**Networks are neither secure nor robust**	●	●		●	●		●			●	●		
12	**Smart automation & technology are hard to justify**	●	●	●	●		●				●		●	●
13	**Innovation is strangled**	●	●	●	●		●						●	●

Table 2 provides a matrix mapping of the key Physical Internet characteristics and the unsustainability symptoms to the reduction of which they contribute significantly. This mapping is subject to judgment since there are interlacing synergistic relationships among the PI enabling characteristics and many impact directly or indirectly multiple symptoms.

4. The Physical Internet: a means toward achieving global logistics sustainability

The Physical Internet vision aims at addressing head on the grand challenge of reverting the huge unsustainability of the current way we transport, handle, store, realize, supply and use physical objects around the world.

It is a complex vision. It has both huge scale and huge scope. Indeed, it involves thousands of enterprises and organizations, and millions of people. Put in place, it would affect positively the lives of most people on the planet.

The vision is paradigm breaking. Yet, technologically, nothing in it can be considered as science fiction. Every single one of its constituents is within technological reach. In fact there are numerous projects and initiatives around the world that take a shot at some of its facets: multimodal initiatives, the European green corridor, city logistics and urban mobility initiatives, logistics pooling initiatives, collaborative supply chain projects, green vehicle initiatives. The list could go on.

Such initiatives are necessary yet not sufficient. There is a need for a macroscopic, holistic, systemic vision offering a unifying, challenging and stimulating framework. That is the role intended for the Physical Internet vision.

There is a need for an interlaced set of global and local initiatives, building on the shoulders of current assets and projects, so as to evolve from the current globally unsustainable state to a desired globally sustainable state.

It is important to affirm clearly that the widespread development and deployment of the Physical Internet will not be achieved overnight in a Big-Bang logic. The progression towards making the vision a reality has rather to operate according to an ongoing logic of cohabitation and progressive deployment, propelled by the actors integrating gradually the Physical Internet ways and finding ever more value in the usage and exploitation of the emerging Physical Internet.

There needs to be a smooth gradual transition starting with rethinking and retrofitting phases, then moving toward more transformative phases.

Certification can be a powerful leverage for helping constitute the Physical Internet. Helpful are multi-level certifications of protocols, containers, handling and storage technologies, train stations, ports, multimodal hubs, distribution centers, distribution centers, information systems (e.g. reservation, smart labels, portals), urban zones and regions, and inter-country borders.

5. Conclusion

This paper has outlined a bold paradigm breaking vision for the future of how physical objects are transported, handled, stored, supplied, realized and used across the world. It proposes to exploit the Internet, which has revolutionized the digital world, as an underlying metaphor for steering innovation in the physical sphere. The outlined Physical Internet does not aim to copy the Digital Internet, but to inspire the creation of a systemic wide-encompassing vision capable of providing real sustainable solutions to the symptomatic problems created by the past and current ways and by the current paradigmatic beliefs driving our future undertakings. Reaching global logistics sustainability is grand challenge. The conception and implementation of the Physical Internet as a solution to this grand challenge is in itself a grand undertaking.

Through this paper and its underlying research, a small step has been made. A lot more are needed to really shape the vision and, much more important, to give it flesh through real initiatives and projects so as to really influence in a positive way the collective future. This will require a lot of multidisciplinary collaboration among and between academia, industry and government across localities, countries and continents.

The domain scope for future Physical Internet research, development and innovation is wide. It encompasses the fields of logistics, transportation, supply chain management and operations research; industrial, mechanical, civil, software and automation engineering; information and communications technology; as well as the business, human, legal, social and urban fields to name a few.

Every characteristics of the Physical Internet needs to be further researched. There needs to be creative design and engineering projects; analytical studies; simulation and serious gaming based projects; pilot, prototyping and demonstration projects; as well as optimization studies for decision making within the new paradigm. Research can be focused on specific application areas such as containers, handling systems, ports, hubs, and so on. Research can focus on the Physical Internet infrastructures, protocols, enabling technologies, or yet focus on its usage and exploitation by logistics, transportation, manufacturing, distribution and retailing users. Research can be rather focused on urban, regional, national, continental or intercontinental perspectives.

The paper has focused on the Physical Internet dealing with physical objects, excluding people. The freight scope is huge by itself and justifies this limitation at the current time. Yet, at minimum, it is important in any implementation to insure adequate relationship and integration with people mobility. Ultimately, the Physical Internet would smoothly deal with both freight and human mobility. Obviously, people would not be containerized as freight. Yet conceptually there are many avenues that could lead to the same effect. As a spark toward further exploration, consider a public transport infrastructure where people would take place in nicely designed π-container-size carriers that could exploit the Physical Internet means to move people within and across building, cities, regions and continents, in a fast, safe, secure, ergonomic, green, cheap, elegant and fun way, indeed in an economically, environmentally and societally sustainable way.

Acknowledgements

Numerous researchers have contributed to help the author introduce the Physical Internet as presented in this paper through rigorous comments and stimulating discussions. Sincere thanks to all of them: in Europe, colleagues Eric Ballot and Frédéric Fontane from Mines ParisTech, Rémy Glardon from EPFL, Detlef Spee from Fraunhofer Institute for Material Flow and Logistic, and Rene De Koster from Erasmus University; in America, colleagues Russell D. Meller from University of Arkansas, Kevin Gue and Jeff Smith from Auburn University, Kimberley Ellis form Virginia Tech, Leon McGinnis from Georgia Tech and Mike Ogle from MHIA; at the CIRRELT research center in Canada, colleagues Teodor Crainic from UQAM, Michel Gendreau from Université de Montréal, as well as, from Université Laval, colleagues Olivier Labarthe, Mustapha Lounès and Jacques Renaud, and graduate students Driss Hakimi, Hamza Heni, Christelle Montreuil, Salma Naccache and Helia Sohrabi.

The Canada Research Chair in Enterprise Engineering, the Discovery Research Grants Program of Natural Sciences and Engineering Research Council, and the College-Industry Council on Material Handling Education have provided financial support to this research.

In an effort to stimulate open innovation toward the Physical Internet, a Physical Internet Manifesto has been created and is regularly updated by the author. It is made publicly available at the www.physicalinternetinitiative.org website. In a slideshow mode, it presents and illustrates the Physical Internet vision detailed in this paper.

References

1. Kurose J., Ross K. and Wesley A. “Computer Networking: A Top Down Approach Featuring the Internet”, 5th edition., Addison-Wesley, U.S.A., March 2009.
2. Parziale L., Britt D.T., Davis C., Forrester J., Liu W., Matthews C. and Rosselot N. “TCP-IP Tutorial and Technical Overview”, 2006. http://www.redbooks.ibm.com/redbooks/pdfs/gg243376.pdf
3. U.S. Department of Transportation, “National Transportation Statistics 2009”, Bureau of Transportation Statistics, Washington, D.C., U.S.A., 2009.
4. Warehousing in North America — 2007: A Summary of Market Size, Major 3PLs, Benchmarking Prices and Practices. Armstrong & Associates, Inc., Stoughton, WI.
5. Duong O. and M. Savy, "Prospective fret 2030," MEEDDAT, Paris, 2008.
6. Levison, M., “The Box: How the Shipping Container Made the World Smaller and the World Economy Bigger”. Princeton University Press, Princeton, NJ, U.S.A., 2006.
7. U.S. Department of Transportation, “FAF2 Freight Traffic Analysis”, Federal Highway Administration, Washington, DC., U.S.A., 2009.
8. U.S. Department of Transportation, “Freight Facts and Figures 2009”, Federal Highway Administration, Washington, DC., U.S.A., 2010.
9. Ballot E. and F. Fontane, "Rendement et efficience du transport: un nouvel indicateur de performance," Revue Française de Gestion Industrielle, vol. 27, 41-55, 2008.

10. McKinnon A., “Road transport optimization” Chap. 17 in Global Logistics New Directions in Supply Chain Management, Ed. by Donald Water, The Chartered Institute of Logistics and Transport, Kogan Page, London, UK, 2007.
11. Wilson R.A. “Economic Impact of Logistics”, Logistics Engineering Handbook, edited by G. D. Taylor, CRC Press, Boca Raton, Fl, U.S.A., 2008.
12. Johnston S.L. III, Consequences of Insomnia, Sleepiness, and Fatigue: Health and Social Consequences of Shift Work “, Medscape CME, http://cme.medscape.com/viewarticle/513572_2
13. Crainic, T.G. and Kim, K.H., “Intermodal Transportation”, Chapter 8 in Transportation, Handbooks in Operations Research and Management Science, volume 14, edited by C. Barnhart and G. Laporte, Elsevier, Amsterdam, 367-428, 2007.
14. Crainic, T.G., “City Logistics”. In Chen, Z.L. and Raghavan, S. (eds) Tutorials in Operations Research 2008. State-of-the-Art Decision Making Tools in the Information-Intensive Age, INFORMS, Hanover, MD, U.S.A., 181-212, 2008.
15. Peck H., “Supply chain vulnerability, risk and resilience”, Chap.15 in Global Logistics (5th edition), Edited by D. Waters, Kogan Page, London, UK, 2007.
16. Joint Transport Research Centre, “Security, Risk Perception and Cost-Benefit Analysis: Summary & Conclusions”, Discussion Paper #2009-6, OCDE and Internaitonal Transport Forum, March 2009.
17. Myerson J.M. “RFID in the Supply Chain - A Guide to Selection and Implementation”, Auerbach Publications, Boca Raton, Fl, U.S.A., 2007.
18. “The physical internet: A survey of logistics”, The Economist, The Economist Newspaper Limited, June 17th, London, England, 2006.
19. Kurose J., Ross K. and Wesley A. “Computer Networking: A Top Down Approach Featuring the Internet”, 5th edition, ISBN 0-13-607967-9, Pearson Addison-Wesley, 2010.
20. Parziale L., Britt D.T., Davis C., Forrester J., Liu W., Matthews C. and Rosselot N., “TCP-IP Tutorial and Technical Overview”, 2006. http://www.redbooks.ibm.com/redbooks/pdfs/gg243376.pdf
21. Montreuil, B., R. D. Meller and E. Ballot, "Towards a Physical Internet: the impact on logistics facilities and material handling systems design and innovation," in Progress in Material Handling Research, Edited by K. Gue et al., Material Handling Industry of America, 23 p., 2010.
22. “IEEE Guidelines for 64-Bit Global Identifier (EUI-64) Registration Authority,” http://standards.ieee.org/regauth/oui/tutorials/EUI64.html
23. Johnson M. E., “Ubiquitous Communication: Tracking Technologies within the Supply Chain”, Logistics Engineering Handbook, edited by G. D. Taylor, CRC Press, Boca Raton, Fl, U.S.A., 2008.
24. Scott D. M., “Electronic Connectivity and Software” Logistics Engineering Handbook, edited by G. D. Taylor, CRC Press, Boca Raton, Fl, U.S.A., 2008.
25. “Building a Smarter Container”, RFID Journal, http://www.rfidjournal.com/article/articleview/655/1/1/ , Nov. 19, 2003.
26. Floerkemeier, C.; Langheinrich, M.; Fleisch, E.; Mattern, F.; Sarma, S.E. (Editors), “The Internet of Things”, Proceedings of First International Conference, IOT 2008, Zurich, Switzerland, Lecture Notes in Computer Science, Vol. 4952, Springer, 378 p., 2008.

27. Montreuil, B., D. Hakimi and O. Labarthe, “Supply Web Mapper”, Proceedings of International Conference on Industrial Engineering and Systems Management, 2009.
28. Hakimi, D., B. Montreuil and O. Labarthe, “Supply Web: Concept and Technology”, Proceedings of 7th Annual International Symposium on Supply Chain Management ,Toronto, Canada, 2009.
29. Caisse S. & B. Montreuil, “Conceptualizing Businesses in the New Economy“, Proceedings of Frontiers of E-Business Research 2005. Finland: Tampere University of Technology and University of Tampere, 2005/09/26-28, p. 786-800.
30. Osterwalder, A., & Y. Pigneur, “Business Model Generation : A Handbook for Visionaries, Game Changers and Challengers”, Wiley, 2010.