TOWARDS A PHYSICAL INTERNET: THE IMPACT ON LOGISTICS FACILITIES AND MATERIAL HANDLING SYSTEMS DESIGN AND INNOVATION

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Abstract

Aiming for a radical sustainability improvement, the Physical Internet has the potential of revolutionizing the fields of material handling, logistics, transportation and facilities design. It exploits the enabling concept of standardized, modular and smart containers as well as the universal interconnectivity of logistics networks and services. Its underlying paradigm shift creates a tremendous breakthrough innovation opportunity for the material handling and facility logistics community in terms of equipment, systems and facility design and operation. This paper provides a primer overview of a key subset of the physical elements serving as the foundation of the Physical Internet infrastructure, classified in three categories: containers, movers and nodes. Each element introduced is characterized and illustrated to enable visualization of their innovative nature. The paper helps uncover a wide variety of potent research avenues.

1   Introduction

The Physical Internet is a new paradigm that has the potential of revolutionizing, notably, the fields of material handling, logistics and facilities design. The motivation for this paradigm shift is based on the claim that, "the way physical objects are moved, handled, stored, realized, supplied and used throughout the world is not sustainable economically, environmentally and socially" [1].

To support this claim, Montreuil [1] presents thirteen bold "unsustainability symptoms." For example, vehicles, carriers and facilities are often substantially under- or

wrongly-utilized. As an illustration, road based freight transportation services have been shown to have a less-than-10% overall efficacy [2]. Furthermore, truckers have become the modern cowboys, fast and reliable multimodal transport is mostly a dream, and intra city logistics is generally a nightmare with congested infrastructures not designed to ease logistics.

Overall, modern economies have increased their dependence on transportation and logistics. This is leading to exponential growth in freight flows. For example, in France a freight transport growth of 37% is expected from the 2005 to the 2025 horizon forecasts [3] and the progression is the same for OECD countries [10]. In developed countries, freight transportation is already responsible for nearly 15% of greenhouse gas emission such as CO_2 and this ratio increasing while there are significant reduction goals [11].

In face of these symptoms, the goal of the Physical Internet is to "enable the global sustainability of physical object movement, handling, storage, realization, supply and usage" [1].

The Physical Internet combines standardized, modular and intelligent containers with new logistics protocols and business models, resulting in a collaborative, highly distributed and leveraged logistics and distribution system. In this framework, goods are containerized in containers of modular dimensions and, as data packets in the Digital Internet, are routed using their Physical Internet identifier towards their destination using highly efficient, shared transportation, storage and handling means.

Through the development of a suite of protocols and of container standards, the aim of the Physical Internet is to shift from a fragmented hard-to-optimize organization to an open, distributed organization.

The paradigm change proposed through the Physical Internet is that logistics as currently based mostly on closed operational networks with heterogeneous means should be rethought as a system like the Digital Internet where networks would be interconnected through a common operating framework easing the breakdown of transport and handling loads. This enables, for example, the convenience of less-than-truckload at the cost of full-truckload transportation. The Physical Internet allows progressively integrating currently dedicated logistics networks into a universally interconnected system.

For the logistics service provider, handling shipments of standardized containers that do not need to follow the same route enables locally focused, highly utilized resources.

The deployment of the Physical Internet will inevitably lead to a profound reorganization of transportation and logistics networks and resources. It will also have huge impact on the way the goods, valued by people around the world, will be designed, produced and distributed to cities and households.

The radical transformation of maritime transport unleashed by the introduction of the cargo container [9], with its huge impact on vessels, ports and lifting equipment, provides

a vivid prelude example of the innovation potential offered by a worldwide Physical Internet.

This paper focuses on the impact of the Physical Internet on logistics facilities and material handling systems design and innovation. It is structured as follows. Section two proposes a basic typology of the physical elements of the Physical Internet. The following sections three to five then focus on specific key types. The last section provides conclusive remarks and avenues for further research. The overall paper is conceived as a primer on the logistics facilities and material handlings systems that are expected to be building blocks on the Physical Internet.

2   Physical Elements of the Physical Internet

The three key types of physical elements enabling the Physical Internet introduced in this paper are the containers, the nodes and the movers, as can be seen in Figure 1.
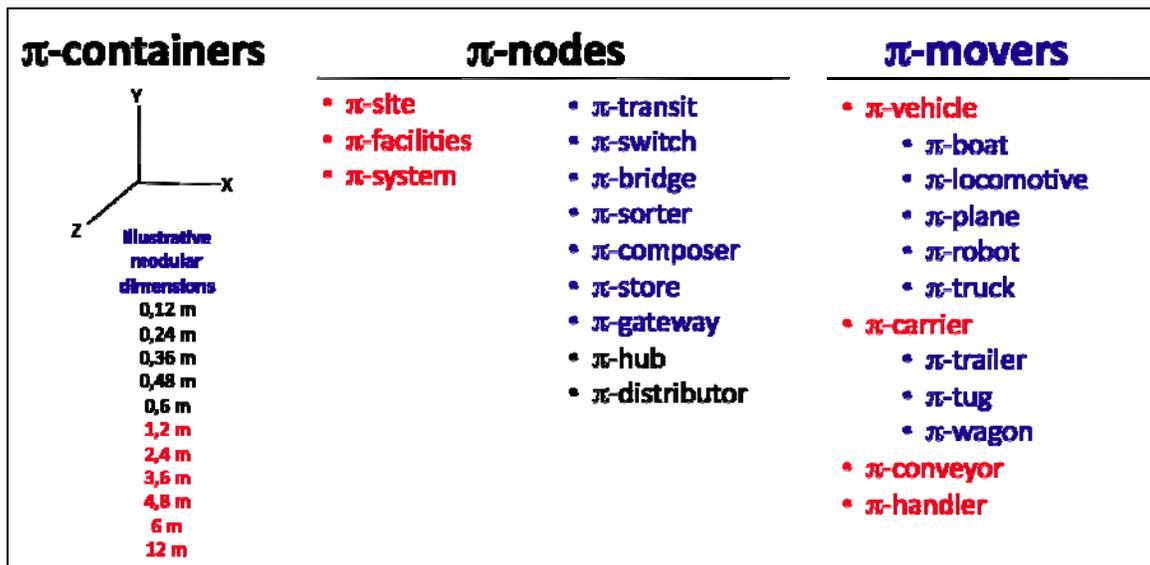

Figure 1. Key types of physical elements of the Physical Internet introduced in this paper

Containers are the fundamental unit loads that are moved, handled and stored in the Physical Internet. As illustrated in Figure 1, Physical Internet containers come in modular dimensions. The nodes correspond to the sites, facilities and physical systems of the Physical Internet. Figure 1 identifies a set of node types that are introduced in this paper. The movers transport, convey or handle containers within and between nodes of the Physical Internet. They also come in a variety of types, as highlighted in Figure 1. Containers, movers and nodes are respectively addressed in sections three to five.

In presenting the Physical Internet elements, we use the prefix π, as the π symbol corresponds to the Greek letter PI, which happens to correspond to the two-letter abbreviation for the Physical Internet. Therefore, we exploit the prefix π in order to differentiate the entities conceived for the Physical Internet from their contemporary

versions. With adoption of the Physical Internet, this prefix would no longer serve a purpose. Note also that the Physical Internet is not a closed system and therefore a π-container could be in a current container ship and a π-container could even contain pallets.

The physical elements are described in the next sections in their accomplished form for simplicity of presentation purposes. Yet it must be clear that the presented elements do not currently exist and are subject to much further design and engineering. So the stated characteristics of the elements should indeed be perceived as original functional design and engineering specifications.

3   The π-containers of the Physical Internet

The Physical Internet does not manipulate physical goods directly, whether they be materials, parts, merchandises or yet products. It manipulates exclusively containers that are explicitly designed for the Physical Internet and that encapsulate physical goods within them. These containers designed for the Physical Internet are called π-containers.

The π-containers are the unit loads that are manipulated, stored and routed through the systems and infrastructures of the Physical Internet. They must be logistics modules standardized worldwide and defined according to open norms.

They must be designed to facilitate their handling and storage in the physical nodes of the Physical Internet, as well as their transport between these nodes and of course to protect goods.

They act as packets in the digital Internet. They have an information part analogous to the header in the digital Internet. Yet contrary to the digital Internet packets, the π-containers have a physical content and structure rather than being purely informational.

3.1   Physical description of π-containers

From a physical perspective, π-containers must be easy to handle, store, transport, seal, snap to a structure, interlock together, load, unload, build and dismantle.

They may contain individual physical goods, as well as π-containers of lesser sizes, or yet smaller private objects not designed for the Physical Internet. The π-containers encapsulate their content, making the contents irrelevant to the Physical Internet.

As highlighted in Figure 1 and illustrated in Figure 2, π-containers are fundamentally conceived to come in a variety of modular sizes. For illustrative purposes, the dimensional modularity of π-containers can be expressed in height, width and depth through combinations of the following dimensions: 0.12m, 0.24m, 0.36m, 0.48m, 0.6m, 1.2m, 2.4m, 3.6m, 4.8m, 6m, 12m and 18m. Actual modular dimensions will be the subjects of evolving international standards. The work of defining the precise sizes and strengths is to be of utmost importance. It should capitalize on learning from contemporary projects such as the TelliBox [4] and the MegaSwapBoxes [5].
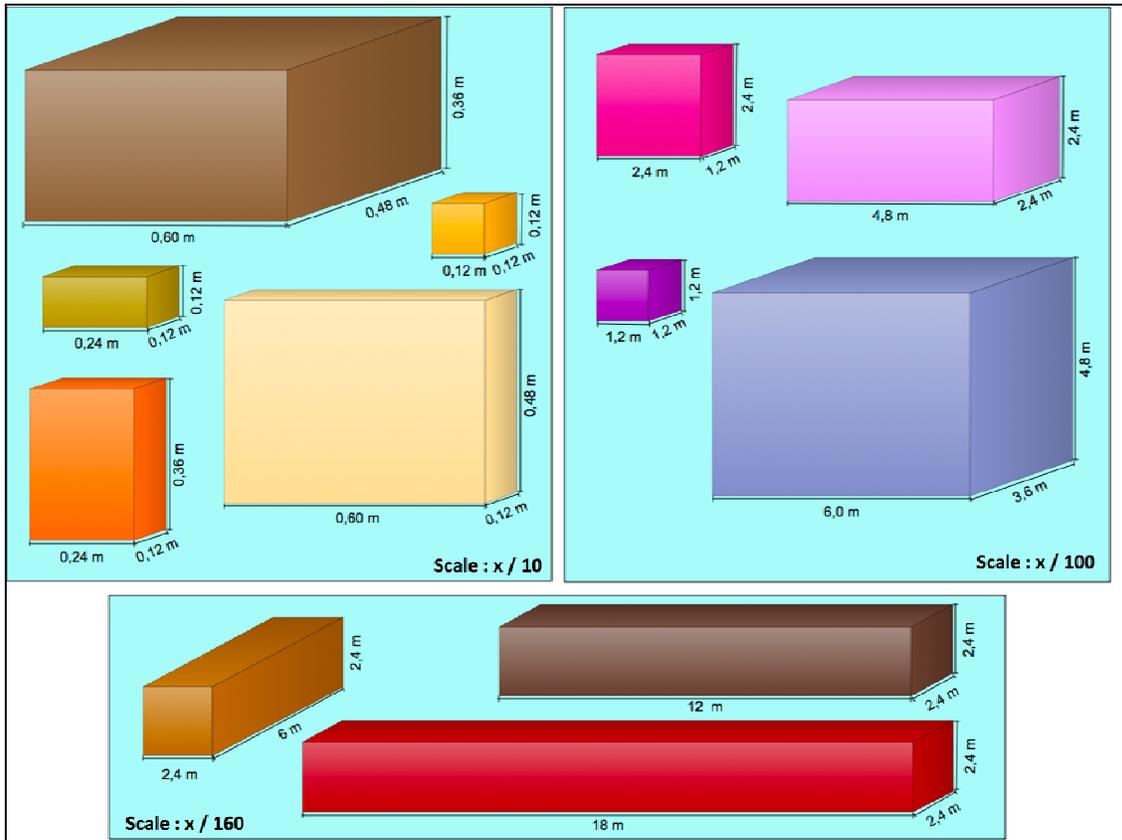
Figure 2. Illustrating some potential modular dimensions for π-containers

The modularity and the interlocking capabilities of π-containers combine to allow the easy composition of composite π-containers from sets of smaller π-containers. The composite π-containers can later be easily decomposed so as to allow the individualized treatment of its constituent π-containers. Such composition is subject to validation of the structural integrity of the resulting composite π-container, depending on its shape and layout, as well as on the structural strength of its embedded π-containers and of the interlocking mechanisms.

The π-containers must have a minimal footprint when out of service, allowing their on-demand dismantling and assembling. They should be as environment friendly as possible, in line with sustainability principles. They must come in a variety of structural grades, adapted to the weight and characteristics of the loads it has to contain, while being as light as possible. They can also have conditioning capabilities such as temperature, humidity and vibration control.

3.2 Informational description of π-containers

From an informational perspective, each π-container has a unique worldwide identifier, such as the MAC address in the Ethernet network and the digital Internet [6]. This

identifier is attached to each π-container both physically and digitally for insuring identification robustness and efficiency.

A smart tag is attached to each π-container to act as its representing agent. It contributes to insuring π-container identification, integrity, routing, conditioning, monitoring, traceability and security through the Physical Internet. Such smart tagging enables the distributed automation of a wide variety of handling, storage and routing operations.

Technically, RFID and/or GPS technologies are currently perceived as being adequate to equip the π-container tags. Yet as with all other elements of the Physical Internet, this will evolve with technological innovations.

Examples of information expected to be in the smart tag of a π-container include:

- Unique identifier of the π-container through the Physical Internet;
- Identifier of the client using the π-container;
- Identifier of the logistician (or of its representative software agent) currently responsible for the π-container;
- Dimensions of the π-container (volume and weight);
- Internal and stack loading structural capacity;
- Functionalities (for handling, storage, etc.);
- Conditioning requirements;
- Identifier of the contract associated with the π-container;
- Status of the π-container (failure/integrity/sealing signals and identifiers);
- Treatment specifications for the π-container (transport from an origin to a destination within some time window, etc.);
- Detailed confidential (or not) information on the content, notably identifying smaller contained π-containers;
- Geo-positioning by GPS or GPRS (when appropriate).

In order to deal adequately with privacy and competitiveness concerns within the Physical Internet, the smart tag of a π-container strictly restricts information access by pertinent parties. The informational contents of π-container tags are protected by a encryption/decryption key for security purposes. Only the information necessary for the routing of π-containers through the Physical Internet are accessible without this key.

The π-container is a key element of the Physical Internet and therefore a lot of research and design work have to be conducted in order to define them for the best fit with π-movers and treatment in π-nodes. This work should build upon contemporary innovative projects on container materials, dimensions and smart tag technologies.

4 The π-movers of the Physical Internet

In the Physical Internet, π-containers are generically moved around by π-movers. Moving is used here as a generic equivalent to verbs such as transporting, conveying, handling, lifting and manipulating. The main types of π-movers include π-transporters, π-conveyors and π-handlers. The latter are humans that are qualified for moving π-containers. All π-movers may temporarily store π-containers even though this is not their primary mission.

The set of π-transporters conceptually includes π-vehicles and π-carriers. These are respectively vehicles and carriers specifically designed for enabling easy, secure and efficient moving of π-containers. They are differentiated by the fact that π-vehicles are self-propelled while π-carriers have to be pushed or pulled by π-vehicles or by π-handlers.

The set of π-vehicles notably includes π-trucks, π-locomotives, π-boats, π-planes, π-lifts and π-robots. These all have contemporary equivalents, yet they differ by the key fact that they are habilitated to operate within the Physical Internet. Similarly, the set of π-carriers includes notably π-trailers, π-carts, π-barges and π-wagons.

Consider the most typical kind of vehicle used in a facility: the ubiquitous lift truck. Such a lift truck takes its reason for existence from the fact that moving goods stacked on a pallet is widely used in current operations. In the Physical Internet, the pallet as we currently know it loses its purpose due to the fact that π-lift-trucks only move and store π-containers that are designed-for-handling, stackable, inter-lockable, and so on. Such π-containers thus have the means to attach themselves to a π-mover without having to be placed on a platform. Thus, the need for forks as currently used to support pallets of goods is removed. π-trucks will gain from innovations exploiting the standard modular π-containers. As an illustration, Figure 3 conceptually depicts a π-lift-truck currently lifting a composite π-container without reliance on a pallet and forks. It exploits a structural frame with gears lockable on the π-container, allowing to hold it and to lift it as desired.
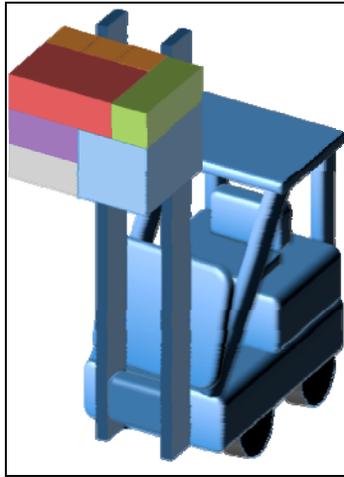
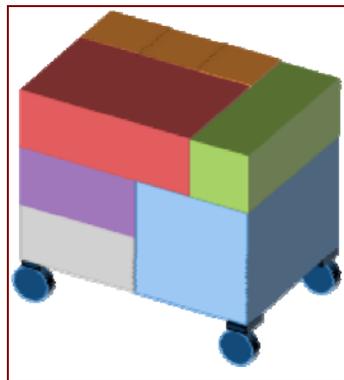Figure 3. π-lift-truck lifting a composite π-container without pallet and forks

Figure 4. Simple illustrative π-mover used for moving a composite π-container

Figure 4 further illustrates how the nature of π-containers may allow simple yet efficient innovations. It depicts a composite π-container with four wheels snapped underneath it so as to allow its manual displacement by a π-handler. The set of four wheels could also be motorized and smart-sensor enabled so as to allow its autonomous travel from origin to destination within the π-facility or π-site. Either manual or automated, it is key to remark that as for the π-lift-truck of Figure 3 there is no reliance whatsoever on a pallet because the π-container is structurally sound and designed for allowing the snapping of handling devices.

Complementary to π-vehicles, the π-conveyors are conveyors specialized in the continuous flowing of π-containers along determined paths without using π-vehicles and π-carriers. Contemporary conveyors typically use belts or rollers to support goods during their continuous flow. Such belts and rollers, with their underlying mechanics,

represent a significant part of the overall cost and physical footprint of the conveyor. As they are explicitly designed for π-containers, π-conveyors may well differ from contemporary conveyors by not having rollers nor belts, the π-containers simply clipping themselves to the π-conveyor gears so as to be towed. They indeed only need an interface to connect themselves to the tracking mechanics of the conveyor core. This simplifies drastically the nature of π-conveyors, while leaving a lot of room for innovation from conveying-solution providers. Note that as contemporary conveyors, π-conveyors may or not be motorized. When not motorized they can potentially exploit gravity or π-handlers to ease the moving of π-containers.
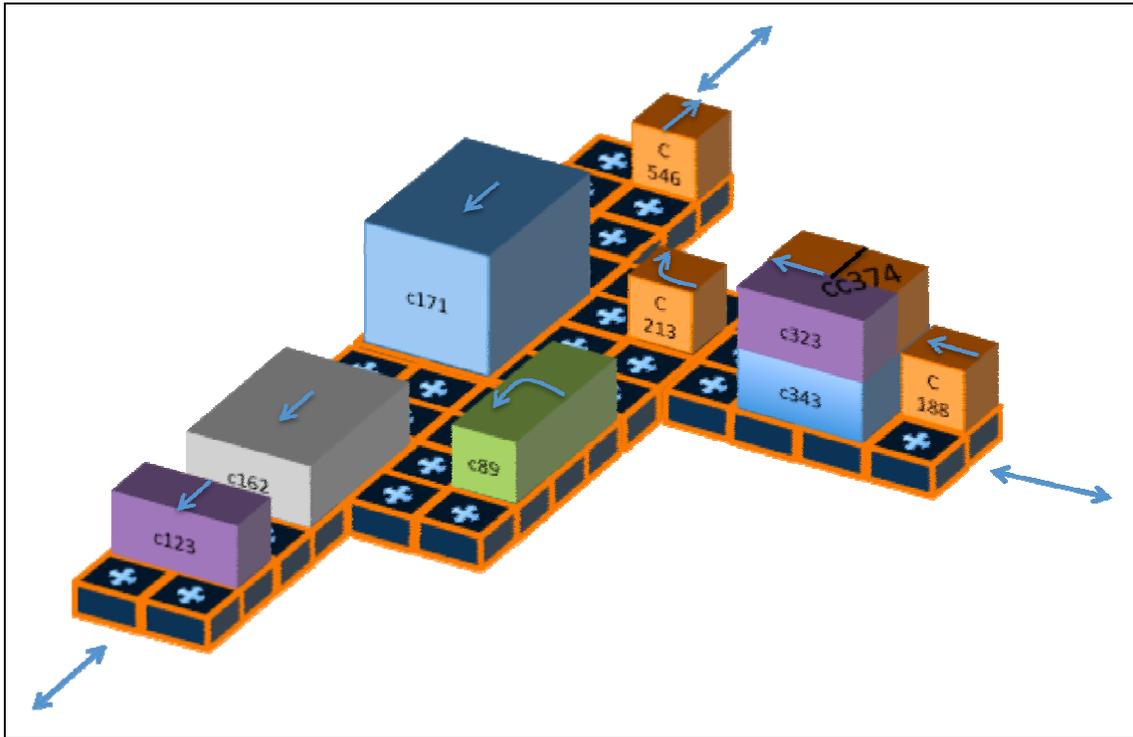

Figure 5. π-conveyor grid composed of flexible conveying π-cells

As an innovative illustration among many possibilities, Figure 5 displays a set of π-conveyors exploiting the recently introduced flexconveyor concept [7, 8]. Here square conveying cells allow moving π-containers in the four cardinal directions. Each cell is dimensioned to the size of the smallest π-container to be conveyed. When only such smallest square π-containers are handled, then each cell autonomously conveys a π-container to one of its up to four neighboring cells. In the example of Figure 5, π-containers of a variety of modular dimensions are conveyed concurrently. This requires coordination of adjacent π-cells for them to act jointly in conveying a large π-container such as π-container c171 occupying a 2X3 grid and having to be conveyed southwestward. Efficient and robust decentralized or centralized algorithms for

controlling a grid of such π-conveyors have yet to be developed. However, examining the design of the grid in Figure 5, which conveys π-containers through a T-shape joint, reveals its conceptual elegancy and potential power. It concurrently conveys a variety of unitary and composite π-containers, each capturing a discrete set of π-cells. Currently all π-containers arrive from the southeast and either want to go southwest or northeast. Currently π-container c89 is standing still for some coordination reason, yet without blocking the main southwest traffic. The traffic pattern could be changed from time to time according to workflow needs.

This section has offered only a primer on the nature of π-movers, with an emphasis on their fundamental essence and the characterization of the basic types. It has provided a few illustrations of the innovation potential. More in-depth examination of π-movers is beyond the scope of this paper and subject for further research.

5   The π-nodes of the Physical Internet

The π-nodes are locations expressly designed to perform operations on π-containers, such as receiving, testing, moving, routing, sorting, handling, placing, storing, picking, monitoring, labeling, paneling, assembling, disassembling, folding, snapping, unsnapping, composing, decomposing and shipping π-containers. There exist a variety of π-nodes delivering services of distinct natures, from the simple transfer of π-carriers between π-vehicles to complex multimodal multiplexing of π-containers.

Generically, the π-nodes are locations that are interconnected to the logistics activities. The activities at a π-node may affect physical changes, such as switching from a transportation mode to another. They may result in contractual changes for the π-containers. To each π-node is associated at least one event for each π-container to ensure traceability of its passage through the π-node.

The π-nodes are publicly rated on a number of key attributes, such as speed, service level adherence, handled dimensions of π-containers, overall capacity, modal interface and accepted duration of stay. Clients will use this kind of information for decision making relative to π-container deployment. Other pertinent Physical Internet entities will also exploit it for routing purposes, through the Physical Internet routing protocol.

Figure 6 illustrates the dynamics of a π-node by displaying its dynamic occupancy in face of arriving and then departing π-containers. For each π-container, Figure 6 provides its realized arrival and departure times, as well as the estimates provided through the Physical Internet routing protocol on its earliest and latest arrival and departure times to ensure the final delivery on time for the client. Figure 6 makes it clear that in the Physical Internet, π-nodes treat π-containers on an individual basis, each having its own contract.
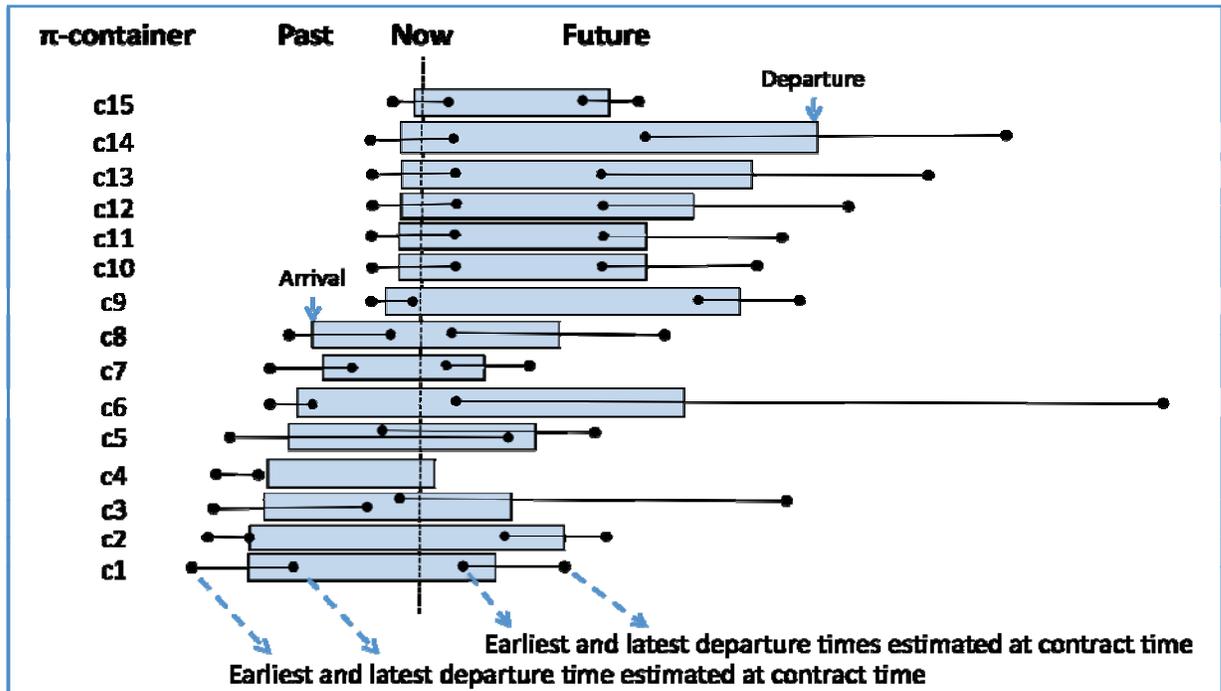
Figure 6. Illustrating the dynamics of a π-node with uncertain
π-container arrival and departure times at contract time

Generically, π-nodes conceptually encompass π-sites, π-facilities and π-systems that are respectively sites, facilities and systems designed to act as physical nodes of the Physical Internet. Usually, π-sites include π-facilities and external π-systems, while π-facilities contain internal π-systems.

The π-node types presented hereafter vary in terms of mission orientation, scope and scale, as well as in terms of capabilities and capacities, yet they all have in common that they are explicitly specialized to treat π-containers at the physical and informational levels.

5.1   The π-transits

The π-transits are π-nodes having the mission of enabling and achieving the transfer of π-carriers from their inbound π-vehicles to their outbound π-vehicles. They allow the distributed transport of π-carriers by a series of π-vehicles, each responsible for a segment of the overall route from primary source to final destination. π-transits aim to ensure the efficient, easy, safe and secure execution of these activities for significant flows of π-vehicles and π-trailers. The π-transits are generally either π-sites or π-facilities, requiring low investment in π-systems.

In road-based transportation, a π-transit can be as simple as a π-site located nearby the intersection of two highways, where π-trucks carrying π-trailers register their arrival, unhook their π-trailer at an assigned location, then either leave or pick up another assigned π-trailer stationed at a location within the π-transit. In general, π-transits are often unimodal. There can be multi-modal π-transits. For example, π-trailers can be transited from π-trucks to either π-trains or π-boats, and vice-versa.

Figure 7 illustrates a simple π-transit composed of ten π-bays, each allowing the parking of one π-carrier. Each arriving π-vehicle backs up its π-carrier into an assigned π-bay when it becomes available. Then it either departs or moves to attach another assigned π-carrier and then departs with this new π-carrier. A π-vehicle may come in just to pick up an assigned π-carrier. Figure 7 shows graphically the current state of the illustrative π-transit. It also provides a table indicating both the current physical and informational states of the π-transit. For each π-carrier, it states the π-carrier that brought it, its arrival time, the π-bay it is parked in, the π-carrier expected to pick it up, as well as the estimated earliest, most probable and latest times at which it is to be picked up. The π-transit would also have a similar log of all π-carriers it has a contract for taking care of its transit, but that are not yet arrived. In such a log the arrival time would be an estimate as shown in Figure 7 for the departure time.

The π-transits enable distributed transportation of π-carriers. Along the route from origin to final destination, a π-carrier can for example be iteratively transported from its current π-transit to a π-transit located a few hours away. This helps greatly to reduce the pain endured by truck drivers currently having to be far from home for weeks due to long hauls. In the process, they also help reducing the traveling time as the π-carrier only have to wait a coordinating time at each π-transit rather than having to stand still long hours while the driver gets his meals and his sleep. This illustrates that despite their simplicity the π-transits improve logistics performance in many aspects.

5.2   The π-switches and π-bridges

A π-switch is a π-node having for mission to enable and achieve the unimodal transfer of π-containers from an incoming π-mover to a departing π-mover. Examples include rail-rail π-switches and conveyor-conveyor π-switches. There is no multiplexing. There is rather an essentially linear transfer.

A π-bridge is a π-node having a mission of the same type as a π-switch, specializing in the one-to-one multimodal transfer of π-containers not involving any multiplexing. An example is a rail-route π-bridge.

The main tasks of a π-switch and a π-bridge are double. From a physical perspective, their main role is the efficient, safe, secure and reliable transfer of π-containers from one π-mover to another. From an informational perspective, their main

role is ensure that the receiving π-mover is ready before the π-container is transferred, that all parties are informed of the transfer, and that the contracts are terminated and activated respectively for the incoming π-mover and the departing π-mover.
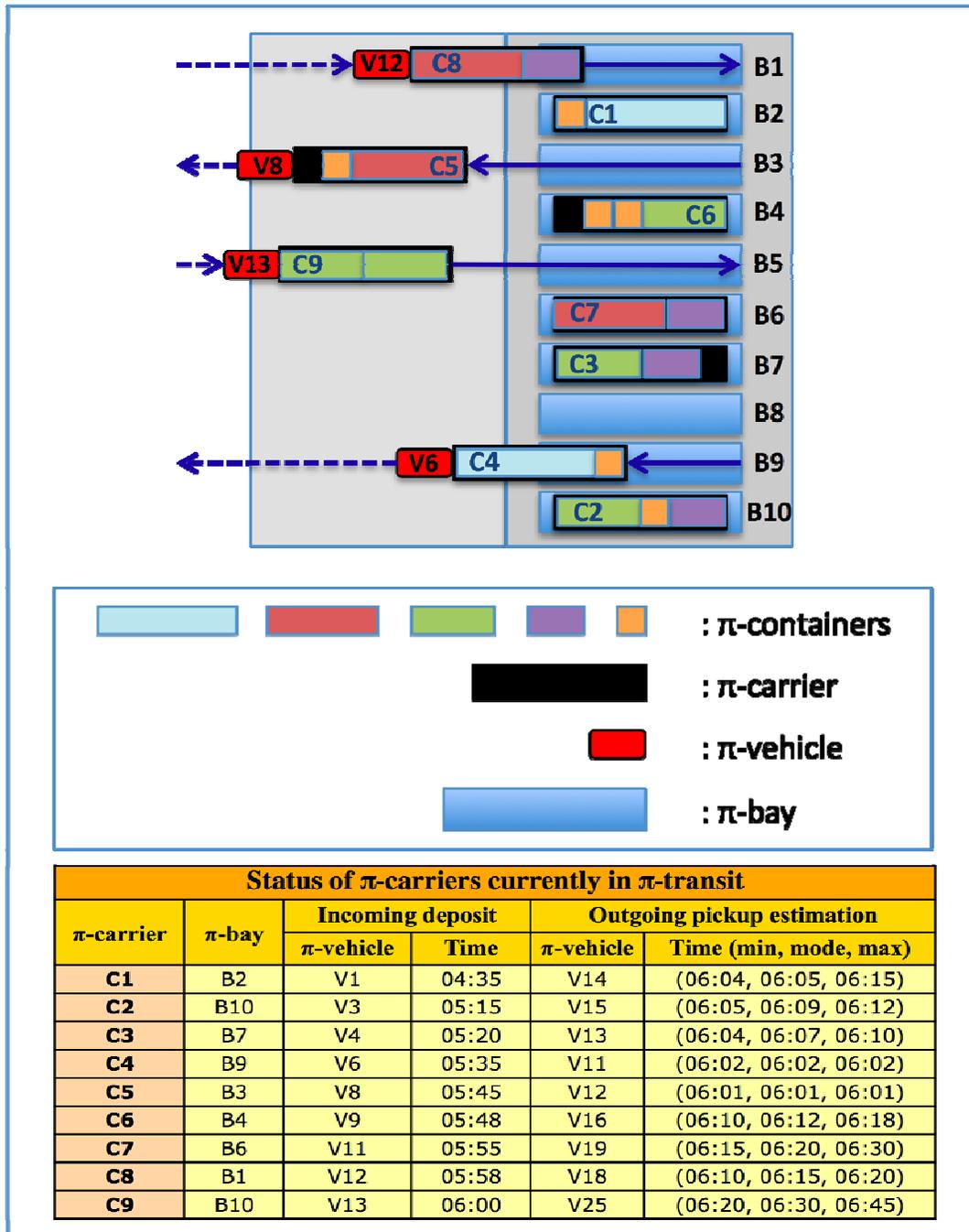

Status of π-carriers currently in π-transit					
π-carrier	π-bay	Incoming deposit		Outgoing pickup estimation	
		π-vehicle	Time	π-vehicle	Time (min, mode, max)
C1	B2	V1	04:35	V14	(06:04, 06:05, 06:15)
C2	B10	V3	05:15	V15	(06:05, 06:09, 06:12)
C3	B7	V4	05:20	V13	(06:04, 06:07, 06:10)
C4	B9	V6	05:35	V11	(06:02, 06:02, 06:02)
C5	B3	V8	05:45	V12	(06:01, 06:01, 06:01)
C6	B4	V9	05:48	V16	(06:10, 06:12, 06:18)
C7	B6	V11	05:55	V19	(06:15, 06:20, 06:30)
C8	B1	V12	05:58	V18	(06:10, 06:15, 06:20)
C9	B10	V13	06:00	V25	(06:20, 06:30, 06:45)

Figure 7. Illustrative simple π-transit

5.3   The π-hubs

The π-hubs are π-nodes having for mission to enable the transfer of π-containers from incoming π-movers to outgoing π-movers. Their mission is conceptually similar to the mission of π-transits, but dealing with π-containers themselves rather than dealing strictly with the π-carriers. They enable unimodal π-container crossdocking operations. Furthermore, π-hubs will be at the core of fast, efficient and reliable multimodal transportation, by allowing ease of transfer of π-containers between combinations of road, rail, water and air transportation.

Figure 8 provides a simple π-hub example. In this case, π-containers come either on a π-boat or on a π-trailer pulled by a π-truck. The π-hub is laid out so that incoming π-boats enter a bay where they are anchored so as to allow π-container loading from one side and π-container unloading from the other. The implemented operational dynamics lead the π-hub operators to prepare π-containers on the appropriate quay for easing their loading prior to their π-boat arrival. Once a π-boat arrives, its π-containers having to be transferred to road based transportation are unloaded and then either routed directly to a waiting π-trailer or to a buffering π-store (here identified as a dark green rectangle) awaiting the arrival of their assigned road based π-mover. When the spatially conflicting π-containers have all been unloaded from the π-boat, then the loading of its assigned π-containers is started, eased by the fact that many have been smartly put aside the π-boat on the quay. From the other direction, when a π-container arrives on a road based π-mover, it is unloaded and routed toward a buffering π-store, its departing quay or yet directly its π-boat.

The π-hub of Figure 8 is easy to explain and logical to run, yet it represents a type of hub currently not existing. It has three key differentiators, making it a paradigm breaker. One, it is not limited to only two sizes of containers. Second, it purposefully uses small boats rather than huge cargos. Third, its workflow is streamlined and fast enough that some containers may already be gone before their incoming boat is completely unloaded or reloaded.

In general, the simpler π-hubs disembark π-containers from their inbound π-movers and bring them at locations within π-hubs where they are ready to re-embark on their outbound π-movers. Meanwhile, their inbound π-movers are fed with other π-containers and depart from the π-hub. There is thus a continuous flow of inbound, in-transit and outbound π-containers.

Some π-hubs, for example those involving rail and water-based transportation, may restrict themselves to handle only larger π-containers. For example, they may state that they only handle π-containers having a width and a height of 2.4m, with lengths of 1.2m, 2.4m, 3.6m, 4.8m, 6m and 12m. Other π-hubs may conversely focus on smaller dimension π-containers, while yet others may aim for comprehensive offerings with

minimal dimensional restrictions. These are strategic decisions taken by their owners, based on their business intent.
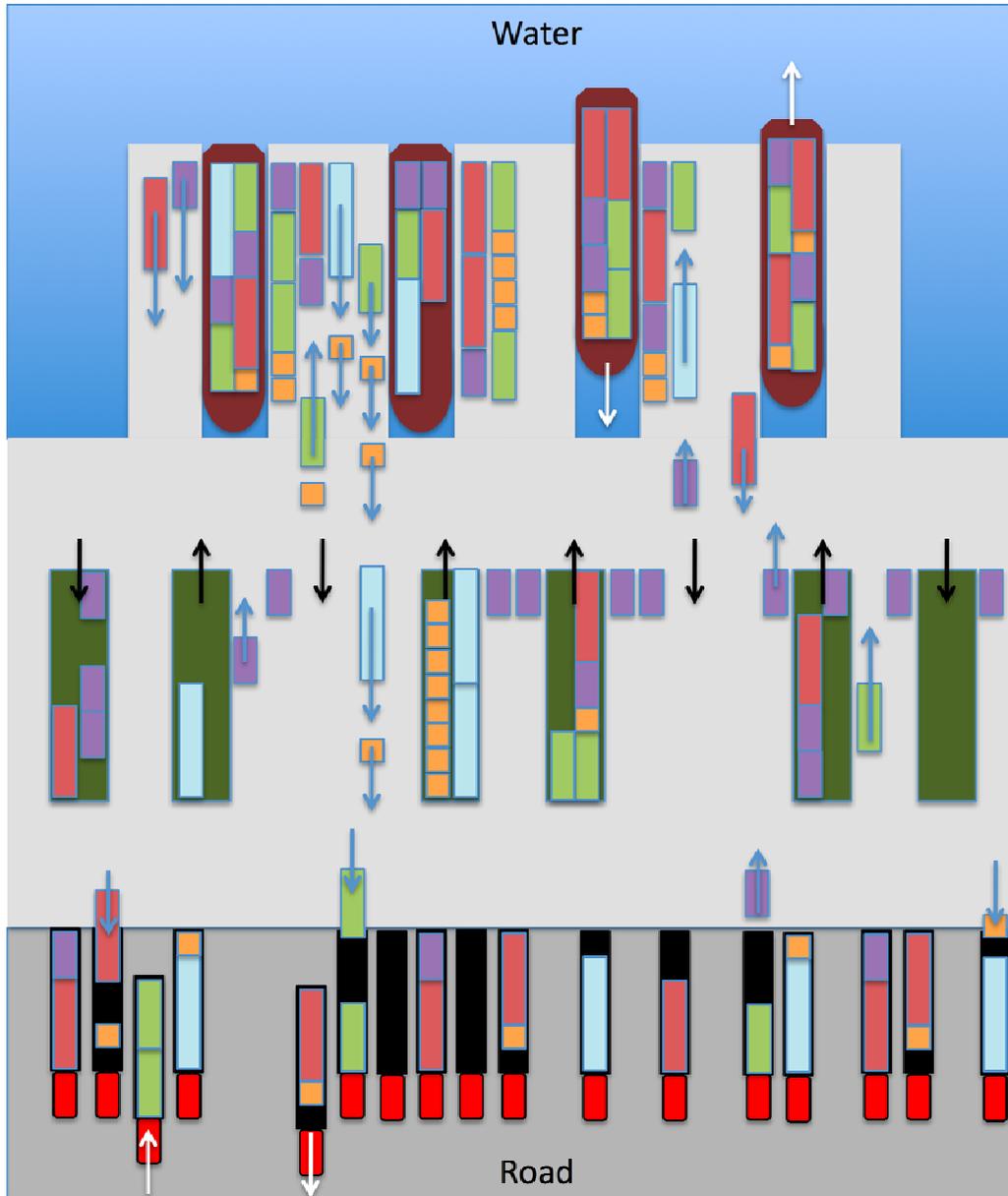

Figure 8. Illustrative water-road π-hub

More complex π-hubs embed π-sorters, π-composers and temporary π-stores. First, π-sorters help sorting the incoming π-containers and channeling them to their assigned π-carrier. Second, π-composers allow incoming composite π-containers to be

decomposed into sets of smaller π-containers, each with its specific target destination and target departure time and π-mover, and composite π-containers to be composed from inbound π-containers and put on departing π-movers, according to client specifications. Third, temporary π-stores allow flexibility in synchronizing π-container arrivals, consolidations and departures.

We hereafter describe generically the π-sorters, π-composers and π-stores that are also key elements of the Physical Internet.

5.4   The π-sorters

A π-sorter is a π-node receiving π-containers from one or multiple entry points and having to sort them so as to ship each of them from a specified exit point, potentially in a specified order. A π-sorter may incorporate a network of π-conveyors and/or other embedded π-sorters to achieve its mission. The π-sorters are typically embedded within more complex π-nodes, such as π-hubs.
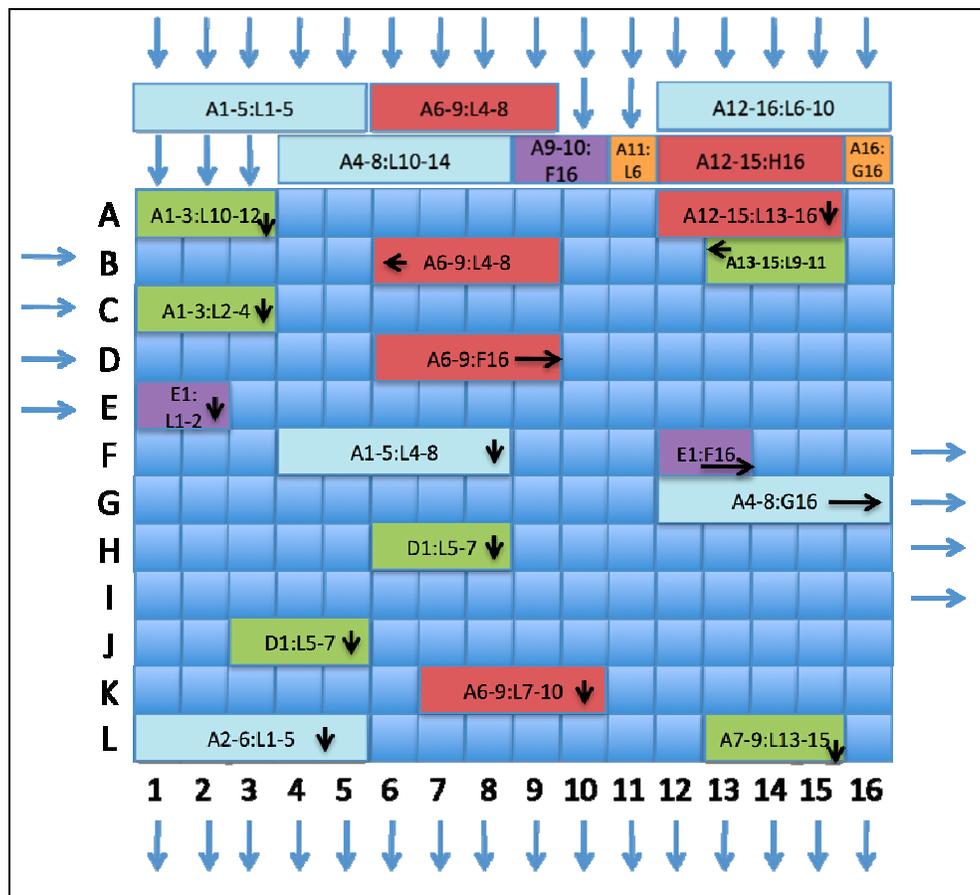

Figure 9. Illustrative matrix-style π-sorter

Figure 9 illustrates a π-sorter built in matrix form with 12 rows and 16 columns. Incoming π-containers reach the π-sorter in the first column of rows B to E and in the first row of columns 1 to 16. They have to be sorted so they reach their specific destination either in some location along the last row L or from rows F to I of column 16. In its current state, the π-sorter has eight π-containers waiting to be sorted and fifteen π-containers actually being sorted. For example, the 1X4 π-container currently in position D6 to D9 entered the π-sorter in positions A6 to A9 and is to be sorted toward outgoing position F16. Such matrix style π-sorters are made a potentially valuable option due to the modular dimensionality of π-containers.

5.5   The π-composers

A π-composer is a π-node with the mission of constructing composite π-containers from specified sets of π-containers, usually according to a 3D layout specified by the end customer or for the purpose of improving efficiency within the physical Internet, and/or of dismantling composite π-containers into a number of π-containers that may be either smaller unitary or composite π-containers, according to client specifications. The composition and decomposition of composite π-containers are respectively realized by snapping together (interlocking) and *unsnapping* its smaller constituent π-containers.
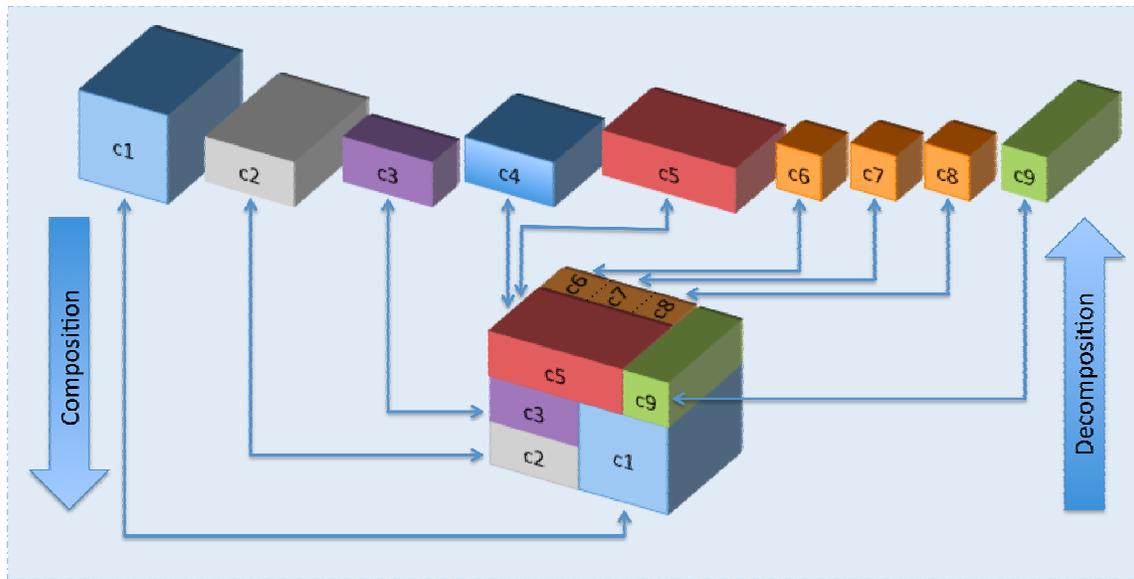

Figure 10. Illustrating the functionality of a π-composer

Figure 10 provides a conceptual illustration of the functionality of a π-composer, depicting nine π-containers interlocked to compose a composite π-container.

The resulting π-container in Figure 10 is a perfect cube with no empty space. Even though spatial modularity of π-containers helps fitting sets of π-containers into a compact composite π-container, it will not be always possible to reach a perfect fit as in Figure 10. In such cases, there are two basic options relative to composition feasibility. First, the holes may be left as such when they are minor and do not impact the structural integrity of the composite π-container. Second, when the holes have significant negative impact on the composition, empty π-container structures can be inserted to fill in the holes. Such modular structures would not need to have closed walls and could be dismantled upon decomposition of the composite π-container.

It is anticipated that π-composers will be designed for composing and decomposing composite π-containers at high velocity. For example, it will be normal to require that a π-composer be able to compose in a few minutes (or less) a 1.2x1.2x6 cubic-meter π-container from twenty smaller π-containers. π-composers are prime candidates for automation, notably integrating π-conveyors and π-sorters. They play a role similar to current palletizers and depalletizers, but with standard easy-to-interlock modular π-containers rather than diverse arbitrarily sized objects that are not necessarily easy to handle. Overall, π-composers perform fragmentation and defragmentation operations on composite π-containers, without ever opening a unitary π-container.

5.6 The π-stores

A π-store is a π-node having the mission of enabling and achieving for its clients the storage of π-containers during mutually agreed upon target time windows. These can be very precise or be more probabilistic, shorter or longer term, as best fit the circumstances. π-stores differ from contemporary warehouses and storage systems on two major points. First, they focus strictly on π-containers: they can stack them, interlock them, snap them to a rack, and so on. Second, they do not deal with products as stock-keeping units (SKUs), but rather focus on π-containers, each being individually contracted, tracked and managed to ensure service quality and reliability.

Figure 11 illustrates the potential stacking and snapping functionalities of a π-store enabled by the fact that it only deals with modular π-containers that are designed for handling and storage.

The left of Figure 11 illustrates a stacking π-store. Stacking is functionally identical to what is being done across the world in cargo container ports, with the added flexibility provided by the dimensional modularity and structural strength of π-containers.
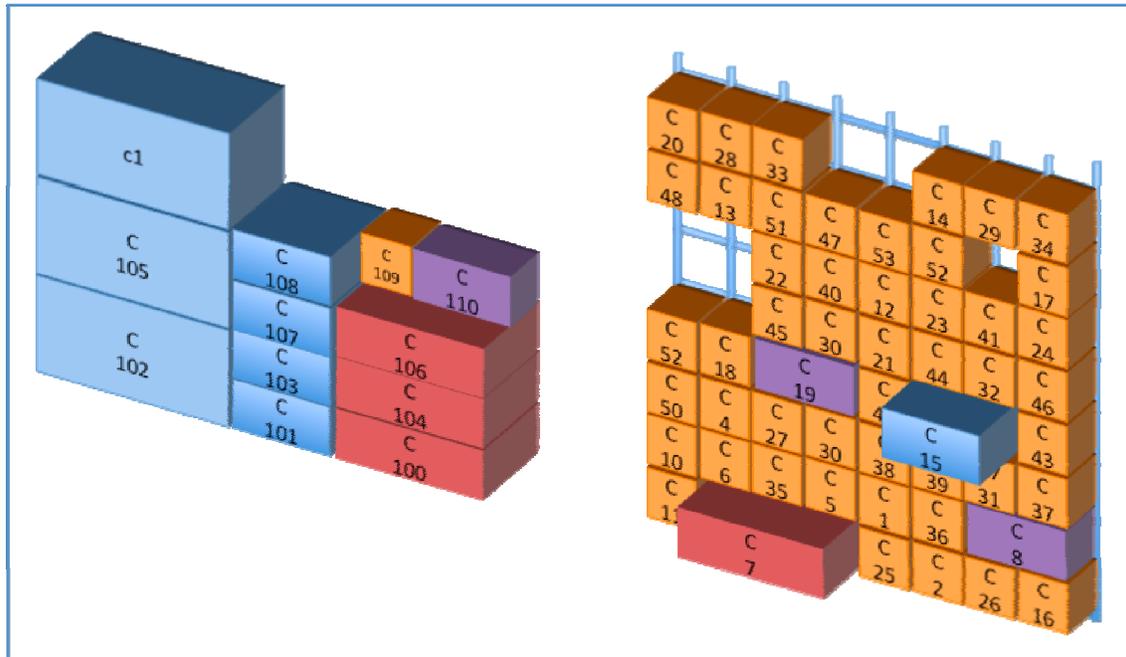
Figure 11. Illustrating stacking and snapping functionalities of a π-store

Clearly, π-containers can be stored in conventional racks, eased by their modular dimensionality, yet they are to lead to new kinds of π-store technologies exploiting the powerful functional characteristics of π-containers and the dynamics of the Physical Internet. As an innovative example, the right of Figure 11 depicts one face of a snapping π-store. Snapping consists of attaching the π-containers to a grid, exploiting fixtures embedded in the π-containers, without having to deposit the π-containers on a flat surface as in conventional rack based storage. The racking cost can be significantly reduced as compared with conventional racking. Indeed a very significant part of any rack today is the platform in each storage slot, allowing cases and pallets to be deposited in the slot. Such platforms are not necessary in snapping π-stores, opening a wealth of innovation opportunities.

Figure 12 expresses the dynamics of a small π-store with four π-bays. At time 3, it stores three π-containers c1, c2 and c3 and has signed a contract for storing π-container c4 in times 4 and 5. Based on the current knowledge in time 3, the planned state of the π-store is shown for times T' = 4, 5, 6 and 7. It shows that if no further contract is signed, the π-store will be empty in time 7. When time 4 comes, the π-store signs two more contracts for π-containers c5 and c6. Then π-container c7 is signed in time 5. The figure adapts the occupancy plan of the π-store as it progresses from time 3 to 5. Here the targeted π-container arrival and departure times are certain for simplifying the

illustration. Note that π-stores are generally subject to more elaborate dynamics in line with the stochastic nature of demand depicted in Figure 6.
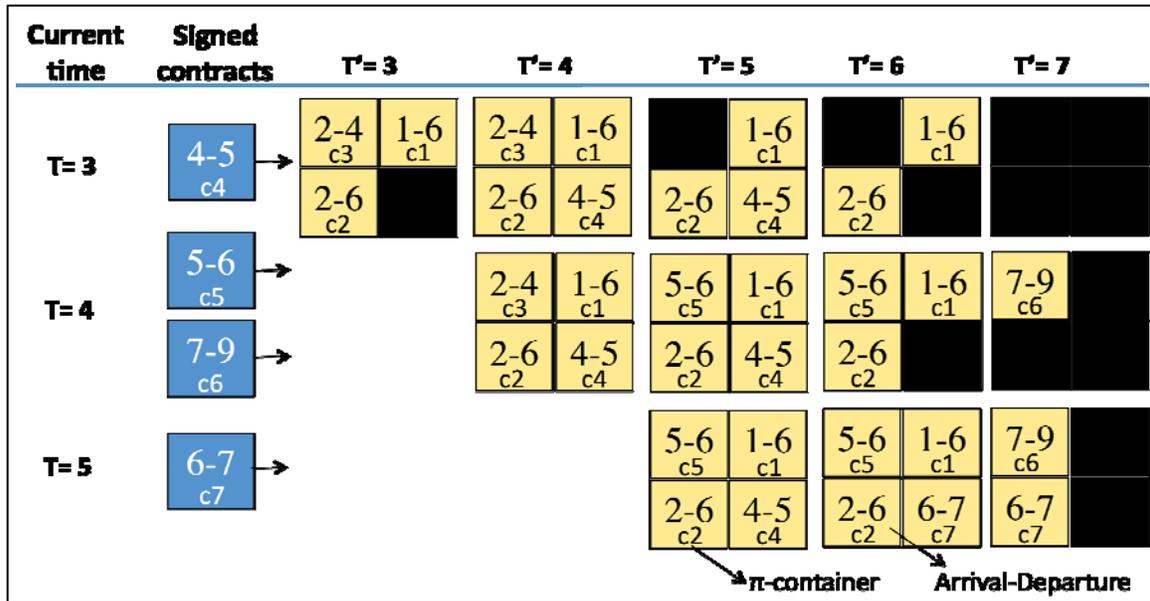
Current time	Signed contracts	T'= 3	T'= 4	T'= 5	T'= 6	T'= 7
T= 3	4-5 c4	2-4 c3 / 1-6 c1 / 2-6 c2 / ■	2-4 c3 / 1-6 c1 / 2-6 c2 / 4-5 c4	■ / 1-6 c1 / 2-6 c2 / 4-5 c4	■ / 1-6 c1 / 2-6 c2 / ■	1-6 c1 / ■
T= 4	5-6 c5 ; 7-9 c6		2-4 c3 / 1-6 c1 / 2-6 c2 / 4-5 c4	5-6 c5 / 1-6 c1 / 2-6 c2 / 4-5 c4	5-6 c5 / 1-6 c1 / 2-6 c2 / ■	7-9 c6 / ■
T= 5	6-7 c7			5-6 c5 / 1-6 c1 / 2-6 c2 / 4-5 c4	5-6 c5 / 1-6 c1 / 2-6 c2 / 6-7 c7	7-9 c6 / 6-7 c7

π-container   Arrival-Departure

Figure 12. Illustrating the dynamics of a small π-store

It is quite possible for a π-store to receive from a client composite π-containers, to have them dismantled, storing its constituent π-containers, then to be requested to ship some combination of the client's π-containers, either independently or jointly as a newly-constructed composite π-container. In such cases, either the π-store embeds a π-composer or exploits a nearby π-composer not part of itself.

In π-stores, capacity and speed for receiving π-containers and shipping them are critical success factors, as well as storage capacity. Their π-container dimensional, security, visibility and conditioning capabilities are other key factors. π-stores come in a multitude of sizes, such as π-storage-systems within facilities, π-storage-facilities, or π-sites storing π-containers outside, such as a π-yard.

5.7 The π-gateways

The π-gateways are π-nodes that either receive π-containers and release them so they and their content can be accessed in a private network not part of the Physical Internet, or receive π-containers from a private network out of the Physical Internet and register them into the Physical Internet, directing them toward their first destination along their

journey across the Physical Internet. For example, a factory that is not internally π-enabled may have π-gateways at its receiving and shipping centers.

Generically, π-facilities of various types may embed π-gateways and tightly contained centers that are not explicitly part of the Physical Internet. For example, a π-distributor may have some focused out-of-PI centers doing some personalizing, value-added operations on some types of products embedded in π-containers, according to client specifications. Such centers may open π-containers and actually work on its embedded objects. π-gateways ensure the exit to and reentry from such an out-of-PI center of π-containers.

The π-gateways have both physical and informational mandates. On the physical side, they ensure the physical integrity of π-containers and their efficient, secure and safe physical transfer in and out of π-movers, π-systems and π-facilities. On the informational side, they interact with the π-container agent so as to validate the π-container identity, the contractual agreements, to initiate tracking as pertinent, to validate π-container sealing when appropriate, to be informed of its first destination within the Physical Internet, and so on.

6 Conclusions

The Physical Internet is both easy to grasp due to its reliance on the analogy with the Digital Internet and difficult to understand due to its complexity and the change of paradigm it implies. This paper attempted to aid with the understanding by defining and discussing a key set of basic physical elements of the Physical Internet.

This set is far from being exhaustive. For example, more complex elements have not been described. For example, π-distributors are the π-equivalent of current distribution centers, yet restricted to π-containers. Potentially, they can embed any combination of the above types of π-nodes. They can perform crossdocking operations such as π-hubs, store π-containers as π-stores, and so on. Describing the characteristics of such complex π-distributors is out of scope for this paper and subject to further research.

Although the set is not exhaustive, there are more physical elements yet to be defined, and a more in-depth characterization and modeling required for all elements, we hope the paper provided a stepping stone towards further understanding, investigation and implementation of the Physical Internet.

The paper also attempted to highlight the great breakthrough innovation opportunity brought forward by the introduction of the Physical Internet. The paper presented the significant innovation opportunity for material handling technology providers and logistics facilities designers. First, it showed how the current nature of fundamental elements such as lift trucks, conveyors and racks is challenged by the Physical Internet. Second, it introduced new types of systems and facilities necessary for the Physical

Internet or enabled by it, such as π-composers. Third, it introduced illustrative instances of π-nodes that challenge the current paradigms, such as the water-route π-hub of Figure 8. Innovation is of paramount importance so as to enable the easy, efficient, robust, safe and secure travel and storage of π-containers through the Physical Internet.

The Physical Internet is about networks of networks, each embedding nodes and links between these nodes, with standard modular containers. Its introduction aims toward a radical improvement in the economical, environmental and social sustainability of worldwide transportation, handling, storage, supply, realization and usage of physical goods. It is through this aim that Physical Internet focused material handling system and logistics facility design and innovation should be addressed.

The paper helps to uncover a wealth of novel and important research avenues. Indeed, every introduced Physical Internet element requires further characterization, modeling, prototyping and testing. The interplay between π-container, π-mover and π-node design and engineering is also an important research avenue. The interplay between the physical, informational and financial facets is again a promising research avenue. The architecture of π-nodes from the core set introduced here and others as needed is a virgin field of exploration. The same is true at the network level and the networks of networks level, investigating the means and impacts of deploying π-nodes of various types so as to best enable the Physical Internet. Finally, there is significant research required on the gradual transformation of the existing sets of containers, movers, systems, facilities, sites and protocols along a roadmap from the current paradigm towards a full implementation of the Physical Internet.

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