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On the value of the Digital Internet / Physical Internet analogy

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Abstract – Classical logistic networks have long since struggled with the increasing demand for flexibility and responsiveness, driven by the emancipation of consumers and the globalization of our world. Hence, since 2010, researchers in the logistics domain propose the ‘Physical Internet’ (PI) as guiding vision for innovations in logistic networks. The PI model adopts concepts and ideas from the ‘Digital Internet’ (DI) world and applies these to the movement and storage of physical products. While researchers have been working with this analogy for the past decade, a debate has emerged about the value of the DI/PI analogy and its usefulness for guiding the design of the PI. Specifically, prior work has not focused on ascertaining the accuracy of the analogy, i.e., how well logistics researchers have adopted concepts from the Digital Internet, and how this may influence the value of the analogy in the current discourse. The aim of this paper is to help fill this gap, using a qualitative research approach. We use 15 semi-structured expert interviews, to determine how well the DI is understood among the experts working on the DI/PI analogy. We propose the Analogy Functionality Model to interpret the results and assess the current strength of the analogy. We find that the strength of the DI/PI analogy varies across functions. Its application value lies particularly in the persuasion of stakeholders, the accessible explanation of key concepts, and the gathering of inspiration for further design directions. This underlines the importance of the analogy for the PI innovation community. Researchers and logistics practitioners should, however, refrain from using the analogy as a blueprint for the design of PI systems. For implementation purposes, we recommend that researchers move to conceptually emancipate the PI from the DI.

Keywords: Physical Internet (PI); physical internet analogy; logistics; analogical reasoning; analogy functionality model

1. Introduction

Modern day logistics networks struggle to keep up with the requirements set for by increasing globalization. They are often fragmented, and interconnections between large logistics networks are often underdeveloped. (Sarraj et al. 2014). Montreuil et al. (2010) describes how this current state leads to inefficiencies. To counter this, they propose a vision in which logistics networks are more economically, environmentally, and socially efficient by modeling them after concepts from the Digital Internet (DI). Montreuil (2011) in fact claims that, after the DI used concepts from the physical world in the 1990s, e.g., the ‘information highway’, now is the time to utilize the metaphor in the opposite direction. Montreuil (2011) sees potential in adopting concepts for modelling the flow of goods along the idea of data packets flowing through the DI, or the use of protocols and standardization in the DI, where they also see parallels to the standardization of maritime transport using ISO containers. To define this novel approach, they coined the term Physical Internet (PI), suggesting a move towards globally hyper-connected logistics networks and more efficient supply chains (Treiblmaier et al. 2016). Since its introduction in 2010, the PI has gained increased traction in both industry and academia. Within a decade, more than 2.000 articles have appeared in literature noting the PI as keyword, with over 27.000 citations (obtained from app.dimensions.ai).

Although the PI is a promising vision, the analogy for research from the DI to the PI has not remained without dispute and its use has not been reported in a transparent and systematic fashion. The analogy was

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operationalized in most detail by Montreuil et al. (2013), who also integrate concepts such as encapsulation, interconnectivity, the open web, and standardized protocols from the DI to the PI. While they used these concepts as inspiration for the PI, we note that the information on how the concepts were derived from the DI is provided on an aggregated level only. This has left it unclear how exactly and to what extent these concepts should be *implemented* in the PI's design. Some authors have explicitly taken the analogy as the starting point for the design of the PI. Sarraj et al. (2014) were the first to use the analogy for network design and state that there are strong similarities between DI and logistics, but also note the differences in the type of objects transported in the different networks. Basing their analogy on the interconnection of networks, the structure of networks, and the routing of objects in these networks, their research remains explorative. In addition, the object of the research is not so much the analogy itself - it takes the analogy as given and builds on it as realistically as possible, with the purpose of taking a step in PI design. Similarly, Arjona Aroca and Furio Prunonosa (2018) use the analogy in terms of hierarchical routing to create an operational model for hubs that aims at easing the creation of routing algorithms for these hubs. Dong and Franklin (2020) also studied the PI on the basis of the DI. They propose a conceptual framework for the PI network routing with the DI as a foundation. They translate eleven elements they identified in the DI into logistics. These elements include actors (users, carriers, and service providers), and actions, e.g., collaboration. Additionally, they identify differences in the DI and the PI related to metrics such as costs, time, and schedules. Most recently the "Roadmap to the Physical Internet" (SENSE 2020) makes several references to the DI and the analogies with physical systems but does not discuss the attributes or the value of the analogy. Amongst the review articles in the literature about the PI related research, only 2 touch upon the analogy explicitly. Sternberg and Norrman (2017) mention the analogy as a central starting point for design of the PI. Citing earlier work, they are critical about the value of the analogy, based on the fundamental differences between physical and digital objects. At the same time, they do not elaborate further on its strengths and weaknesses. Treiblmaier et al. (2020) describe how their results lead to a major question regarding the right approach to realize the PI's vision. They state the DI might be helpful in this case due to its 'layered nature', which allows to improve specific aspects of the DI without disrupting the other layers in the system. They suggest a similar structure could be beneficial for the PI so that researchers can improve specific aspects of the PI without disrupting the whole system. The DI/PI analogy is, however, not subjected to further interpretation.

From the above we can conclude that a debate has formed underlying the research efforts to design the PI, about the extent to which the analogy can be regarded as useful for the development of the PI system. This question has not been asked formally and no attempts have been made yet to formulate answers as to the bounds of applicability of the analogy. Our research aims to help fill this gap.

What prior work on the PI has in common is that the *application* of the identified DI principles remains unclear, and that the source of concepts in the analogy is described in a high-level or aggregate view, making it difficult to assess whether the researchers utilize ground-truth rooted properties of the DI or their own *mental models* of concepts from the DI. Hence, in this paper, we investigate how the community process of creating the analogy inflicts on its value to lead to actual PI *implementations* in practice. We take a qualitative research approach, which due to appropriate coding of interviews and transparent conceptual modelling is entirely tractable. Specifically, we make the following contributions to literature:

- We conduct 15 semi-structured expert interviews and find that the sourcing of concepts from the DI is regularly driven by researchers' own *mental models*, which diverge from the actual concepts in the DI.
- We develop an Analytical Functionality Model (AFM) rooted in literature which we apply to our observations on the state of the DI/PI analogy to assess its value and maturity. While the analogy's strength is limited by fundamentally diverging realities in some respects between the DI and the PI—for example copying of goods being essentially free in the DI—we find that the DI/PI analogy *does* hold value for argumentative, illustrative, and inspirational purposes. The use of the analogy for design purposes should, however, be approached with caution.
- Based on these findings we outline recommendations for the community on how the DI/PI analogy can be used.

We first introduce the problem mapping based on the concept of analogical reasoning in Section 2. We then describe our methodology for the interview study in Section 3 and present the results of the study in

Section 4. We discuss and analyze these results in the context of our AFM in Section 5, and finally conclude with recommendations for the community in Section 6.

2. Conceptual Framework

In this section, we briefly re-iterate the concepts of analogies, analogical reasoning and functionality of analogies. We provide perspectives from the literature on how and when analogies are useful when reasoning about systems, i.e., what function they usually serve. Subsequently, we elaborate which limitations commonly apply to analogies. Finally, we synthesize the Analogy Functionality Model to assess the maturity and value of an analogy.

2.1. Analogies

Kigozi et al. (2014) Analogies, or analogical reasoning, are a common tool used by scientists, teachers, designers and many other professions. The core idea is that in an analogy, two objects or systems of objects are compared according to their similarities. In this comparison, there is a source case from which information or meaning can be transferred to a target case. This comparison is also referred to as mapping, which involves placing different objects and relationships between objects in the analog into correspondence with the target (Krawczyk 2018). After an analogy is mapped, new inferences can be made, also known as an analogical argument. An analogical argument cites similarities between two systems of objects to conclude that further similarities exist between the systems. In an analogical argument, we state that *T* is like *S*, because they share properties *a*, *b*, *etc*. Therefore, *T* probably has property *c* since *S* also has property *c*, see Figure 1. In this context we refer to the *accuracy* of an analogy as to how well *S* and *T* are modelled in the analogy, and to the *strength* of an analogy as to how well the properties of *S* and *T*—and not their models—map to each other.

Figure 1. Mapping in analogical reasoning

While analogical reasoning is most likely one of the oldest forms of reasoning, there are no universal rules on how to construct an analogical argument. Bartha (2019), among others, traces this back to the fact that not every similarity between a source and a target case increases the probability of a conclusion about the target case, as some similarities may be irrelevant. The relevance of a similarity (or a dissimilarity) can only be determined by its context. Despite this, various logicians and philosophers have identified commonsense guidelines for evaluating and interpreting analogies, among which are, Robinson (1930), Stebbing (1930), Moore and Parker (1988), Copi et al. (2018), Walton and Hyra (2018).

The major heuristics we can synthesize from these reflections are that *i)* More relevant similarities result in a stronger analogy, *ii)* More relevant differences result in a weaker analogy, and *iii)* Limited knowledge of the source or the target domain results in a weaker analogy.

2.2. Functions of Analogies

Our literature survey found four different purposes of analogies. These are *persuasion*, *explanation*, *inspiration*, and *design.* Analogies require different levels of strength and accuracy depending on their specific function. In this subsection, we discuss these four purposes, and analyze how much *strength* they require from the analogy.

Persuasion

Analogies can be used with the purpose to persuade. In this instance, an analogy is used as a tool to increase the effectiveness of conveying a message in public speaking and persuasive writing. One may use analogies to make speech or text more memorable, colorful, and interesting as they have the power to clarify and trigger emotional reactions (Krawczyk 2018). There are many examples of how an analogy can help persuade people to come to action or help. Mio et al. (2005) found out that highly charismatic presidents used almost twice as many analogies as low charismatic presidents. These results suggest that analogies are important for inspiring an audience. In this case the *strength* of an analogy is secondary, as long as it remains *accessible* and *relatable* for the target audience.

Explanation

Analogies can be excellent teaching tools and are commonly applied in classroom settings (Krawczyk 2018). Teachers and authors often use analogies and draw on the content provided by a source case. In this situation, one must use a well-understood source case and compare this to a less-understood target case (Curtis and Reigeluth 1984, Duit 1991, Gentner and Holyoak 1997). Comparing two domains enables someone to identify similarities and differences between the source and target case (Gentner and Holyoak 1997, Iding 1997). In this manner, analogies are used as a tool to help people learn who are unfamiliar with the target domain (Duit 1991, Donnelly and McDaniel 2000). For example, Gentner and Stevens (2014) outline how some analogies might be more effective than others when explaining (a particular component of) a new concept. They showed that students who try to understand electric currents understood resistors more clearly when the teacher compared it to a moving crowd, while students understood the working of electric circuits in a battery better when it was compared to flowing water. However, for explanatory purposes it is instrumental that the selected analogy does *not* solidify misconceptions due to insufficient *strength*.

Inspiration

Analogies are known to inspire people to develop new ideas, which is why analogical reasoning can stimulate scientists, designers, inventors, or entrepreneurs to develop new concepts, ideas, or products. Many scientists suggest that the development of new theories depend on an analogy drawn from a different domain (Hadamard 1949). Examples here are computer scientists and mathematicians that developed genetic and evolutionary algorithms inspired by nature (Holland 1992), as natural processes often result in optimization, and many scientists try to understand and model these processes.

Design

Finally, analogical reasoning is a powerful tool of inspiration for creating innovative designs (Chan et al. 2011). When analogies are used to design, it is called design-by-analogy. Many breakthrough ideas in the design area are triggered by analogies where solutions from a source domain are transferred to a target domain (Herstatt and Kalogerakis 2005). As such, analogies are often used to develop creative ideas. A good example is the frequently used brainstorm technique, referred to as *Synectics*, which stimulates problem solvers to look for solutions used on similar problems outside the target domain (Gordon 1961). Making an analogy fosters new inferences and promotes problem-solving in new, often unexpected, insightful ways. However, to prevent misdesigns and misconceptions, the analogy used in this process has to have significant *strength.*

2.3. Limitations of Analogies

While analogies are often used to enhance comprehension and stimulate learning, they can also cause misconceptions. These misconceptions commonly arise when one transfers irrelevant and/or incorrect relations from the source to the target domain (Brown and Clement, 1989, Duit 1991, Zook and Di Vesta 1991, Kaufman et al. 1996). Zook and Di Vesta (1991) conducted an experiment among third-grade students that were taught by the use of analogies. They concluded that these students came up with more incorrect inferences, because they drew irrelevant and/or incorrect relations form the source case. Similarly, Treagust et al. (1998) observed that students often transfer attributes and relations literally, which can also cause misconceptions.

Similarly, analogies may provide a false sense of understanding (Treagust et al. 1998, Gentner and Stevens 2014). When a simple analogy explains a complex matter, one may be satisfied with this simple explanation without fully understanding the target case. As a result, one may have a false sense of comprehension. Likewise, Duit (1991) claims that an analogy is only useful for learning if there is a good comprehension of the attributes and relations in the source domain.

The risk of fixation in terms of analogies describes an over-fitting issue. As previously discussed, analogies may foster the generation of new and creative designs. However, using analogies also comes with the risk of design fixation. Design fixation inhibits creativity as it is triggered by focusing on existing paths and solutions (Chan et al. 2011). When a design is fixated on a source case, there is a risk that irrelevant knowledge is translated to the target case and new ideas or impulses that may come from alternative sources are dismissed.

Another commonly faced difficulty with analogies is that of ambiguity, especially, when it includes high complexity. This may cause the analogy to have different meaning to different people. When audiences interpret analogies differently, it becomes challenging to create a shared understanding of the target domain (Taber 2001). Related to ambiguity, there is the issue of different perspective within an analogy. Here, it might be the case that an analogy could be functional from one perspective but dysfunctional from another. This brings along the risk that the wrong knowledge is transferred from the source to the target case, which may affect the target domain in a negative way (Maclean et al. 1991). An example is the analogy of the information superhighway. This analogy uses physical highways for cars as a source domain and telecommunications infrastructure as the target domain. The analogy gained much attention in the nineties, after Gore (1991) introduced it. Gore used this analogy in his article *Infrastructure for the Global Village*. However, as Borgman (2003) explains, also here it can be argued that the analogy is misleading, since the highway analogy skews the public understanding of who bears the cost of the construction of the Internet. The construction of a physical highway is paid by the government, whereas the Internet was created by a combination of public and private funds. This is an example of where an analogy may be useful for one aspect, but not for another.

As mentioned before, there are no concrete criteria that indicate what a particular attribute or relation has to comply with to be suitable for knowledge transfer. Consequently, it is hard to assess the strength of a specific analogy.

2.4. The Analogy Functionality Model

Different analogies have different levels of strength, and there is a point where an analogy becomes dysfunctional, i.e., not fit for its purpose. Likewise, different purposes have a different influence on the target domain. We reason that, in the case of analogy usage for persuasion or education, the user's aim is often not to design or change the target case. As a result, the changes in the target case will be minor and often indirect. When using an analogy for an inspirational or design purpose however, the user often intents to improve the target case, so the effects on the target case are larger. This means that the higher the influence of the source domain is on the target domain, the stronger the analogy has to be. This entails that different analogy purposes require different levels of strength. For instance, when one uses an analogy for persuasion, the analogy may still be functional when the analogy is of moderate strength, meaning the source domain and the target are only similar to a minor extent. However, when we use an analogy for (detailed) design, the analogy is only functional when the analogy is strong, meaning the analogy has a high number of relevant similarities and a low number of relevant differences. We name this relationship between functionality and required strength of the analogy the Analogy Functionality Model. We illustrate this connection in Figure 2.

The key takeaway from this model is that, based on the influence of the source domain case on the target domain case, at some point, an analogy becomes dysfunctional for a purpose and all purposes that require an even stronger analogy. The specific breaking point is different for each analogy and depends on the number of relevant similarities and differences. In the following, we will explain the empirical application of this model to the case of the DI/PI analogy.

3. Empirical Methodology

To evaluate the *maturity* and *value* of the DI/PI analogy, we first have to characterize its *accuracy* and *strength*. This in turn depends on how researchers who use and develop the methodology understand the source case

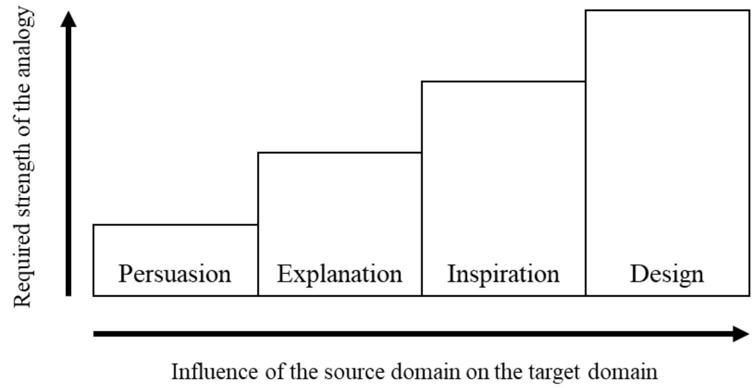

Figure 2. Analogy Functionality Model

from which they import concepts. A person's understanding, i.e., set of beliefs held about a case, is also called the *mental model* this person has of that case. In this section, we first provide context on mental models, and then outline our research approach, including the interview design, recruitment, data analysis, and ethical consideration.

3.1. Eliciting Mental Models

A mental model is a projection of reality, i.e., the image of the world or a concept we hold in our minds (Forrester 1971). Naturally, this model is not complete but consists of selected concepts and relationships. The foundations of the mental modeling approach were laid by Kelly (2020). According to Kelly (2020), a person perceives and interprets events, systems, or objects using his or her own personal construct system. In our case, the PI experts will each have their own reasons to argue for the existence or nonexistence of an analogy between the DI and the PI, based on their mental model of the DI. In our research, we follow the approach by, among others, Zunde and Hocking (2012), who—similar to us—used a mental model approach to investigate a person's understanding of a computer-based system. In their approach, they collected qualitative data in a two-step approach. First, they generated a guiding script of questions and activities to be asked during an interview. They then presented a concept to the participant—in their case three distinct objects of which two were similar—and asked the participant to elaborate on *why* these objects are different. Our research approach was inspired by the work of Zunde and Hocking (2012). We also follow a semi-structured interview script for eliciting mental models, followed by a comparative task. A significant difference between their case and ours is that we aim to find out the comparative mental model of two systems instead of one system's functionalities and relations. We adjust the approach to be applicable to our case. In line with Kelly (2020), we made a shortlist for our interviewees to generate objects to discuss. Subsequently, we asked our interviewees to compare the object they have generated. The experts' mental models give us an idea about how they perceive the analogy between the DI and the PI. Additionally, we validate the perception of the interviewees on the DI against available technical documentation of the features described.

3.2. Interview Protocol Generation and Process

To answer the remaining research questions, we conducted fifteen interviews with PI experts. In these interviews, we use a semi-structured interview protocol (see Appendix A). We choose semi-structured interviews because this provides more freedom of expression to participants, which is necessary to elicit their mental models. To get a comprehensive picture of our experts' mental models, we stimulated them to further elaborate on the analogy by asking about specific elements from the PI. We derived a shortlist of elements from the work of Montreuil et al. (2013), where he describes ten fundamental elements of the PI. From the ten foundations, we generated questions that will help the interviewee to elaborate more. For example, one of the PI foundations listed by Montreuil et al. (2013) are standardized collaborative protocols. We used this to formulate the question: "Do you think there is an analogy on standard collaborative protocols?" As prescribed by Bryman (2012) we tested the protocol with a test group of ten local DI/PI experts in our institution. In these trials, we noticed that several PI foundations lead to confusion among the participants. Hence, we decided to limit the number of concepts we are investigating, focusing on the analogical parts of: *i)* Connecting different networks, *ii)* implementing standardization, *iii)* following protocols, and *iv)* modularization or encapsulation of shipments.

3.3. Recruitment

As the main subject of our research revolves around the PI analogy, and how it is being used and developed, we focused our recruitment efforts on the PI research community. We decided that our sample should ideally cover a wide range of experts, i.e., from academia and industry, as well as participants who predominantly have a background in computer science and those who predominantly have a background in logistics. To attain that sample, we combine targeted recruiting with snowball sampling. For the targeted recruitment, we compiled a list of potential participants from the authors of the most cited publications (via Web of Science and Scopus) on PI and contacted the 18 most relevant authors. Furthermore, for snowball sampling, we attended the ALICE (Alliance for Logistics Innovation Through Collaboration Europe[2]) Conference, where we approached speakers on PI, and solicited recommendations for participants. In total, we recruited 15 participants for our interviews. An overview of their backgrounds and professional roles can be found in Table 1.

Table 1. Overview of interview participants

Participant	Role	Background
I	Non-academic researcher with an interest in innovative ICT solutions for logistics and manufacturing	CS
II	Non-academic researcher, with an interest in supply chain collaboration and cross chain control centers	Logistics
III	Non-academic researcher, with an interest in IT architecture in transport, ports and customs operations	CS
IV	Professor of Industrial engineering with an interest in the role of ports in the Physical Internet	Logistics
V	Professor and head of a national PI initiative with interest in future supply chain and production systems	Logistics
VI	Entrepreneur whose business aims to orchestrate collaboration in supply chains to bundle shipments in the beginning of the chain	Logistics
VII	Professor with an interest in supply chain dynamics, inventory management and production smoothing models	Logistics
VIII	Professor with interest in engaging academic, industry and governments leaders in the PI and further develop the PI	Logistics
IX	Research Fellow with an interest in supply chain innovation and PI realization	Logistics
X	Professor with interest in innovation in information and operation management	CS & Logistics
XI	Lecturer with an interest in the transportation of non-standard goods in the PI	CS
XII	Professor with an interest in coordination for sustainable global supply chain, synchro-modal transport networks and inter-organization systems in logistics	Logistics
XIII	Professor of logistics and academic director with an interest in the application of modern management techniques to supply chains, sustainable business models, green logistics and cloud-based supply chain management	CS & Logistics
XIV	Non-academic researcher with an interest in dynamic transportation systems and transport optimization, healthcare logistics, meta-heuristics and hybridization techniques	CS
XV	Professor in operations management with an interest in industry 4.0, circular supply chains, humanitarian logistics and integrated capacity and inventory management	Logistics

3.4. Data Analysis

For data analysis and coding we used a process inspired by grounded theory (Strauss and Corbin 1997). Specifically, we borrowed the three initial coding steps (open, axial, selective), but—as we do not strive to uncover a new theory—omitted the step of theory generation. Hence, we started with open coding in which we formed

[2] ALICE is the European Commission's Technology Platform on Logistics, with approximately 200 institutional and personal members from industry, academia and government. It provides recommendations for the European R&D funds in the Horizon programs and is the main organization behind the R&D roadmap for the Physical Internet (see etp-logistics.eu).

different code categories. As our research is explorative in nature, we opted to use a single coder (McDonald et al. 2019). The comparison of different categories allowed us to analyze the assumptions of our participants. Secondly, we used axial coding in which we determined the core categories. With these core categories, we then conducted selective coding to identify dominant themes in the DI-PI analogy, according to experts.

3.5. Ethics

We obtained clearance for this research project from our institution's Human subject Research Ethics Council (HREC). The HREC inspected our data management procedures for collected data and ensured that participants are properly instructed about the purpose of the study and their participant rights on the consent form for the study to constitute informed consent. The consent form also explicitly stated that the interviews are recorded and that the participants' names and institutions will be used for the evaluation of the results but not revealed in a subsequent publication, where they are instead replaced by high-level functional characteristics of these positions to provide context for the results.

4. Results

In this section, we first present the similarities and differences between the DI and PI per our participants' mental models. We will then present three examples, which illustrate misconceptions about the workings of the DI and points where the workings of the DI make an analogical transfer of concepts from the DI to the PI difficult.

4.1. Perceived Similarities

We first summarize the perceived similarities between the DI and PI which we identified in the interview transcripts in Table 2. We cluster the perceived similarities based on whether they relate to *attributes* or connect to *relations* between different attributes. The similarities are discussed below.

Table 2. PI experts perceived similarities between DI and PI

Level	Code Group	Mentioned by
Attribute	Similarities in actors, hubs, and modes	I, V, VIII, XIV
	Similarities in packets and packages	I
Relational	Similarities in bundling and splitting	I, II, III V, VII, IX
	Similarities in organization	V, VI, XIII, XIV
	Similarities in standardization	II, VI, VIII, IX, XII, XIII, XIV, XV
	Similarities in automation	III, VII, VI, XI, XV
	Similarities in openness	VI, XIV
	Similarities in user experience	II, IV, VI, XIV, XI
	Similarities in flexibility	I, V, VIII, XIV

Attribute level

We identified two similarities mentioned on the attribute level. Several participants see a similarity between the actors in the DI and PI. **Interviewee I** described both domains as having a sender, a receiver, and a packet or package. **Interviewee V** drew a comparison between transport modes, for example from wired to wireless connections in the DI and from train to ship transport in the PI. **Interviewee VIII** and **Interviewee XIV** described the analogy between a router in the DI and a PI hub. All of our interviewees used the comparison between a data packet in DI to a package or shipment in PI in their line of reasoning. Only **Interviewee I** compared the structure of a data-packed to the structure of a container in the PI.

Bundling and Splitting

Seven interviewees described a comparison between the bundling or splitting of packets in the DI to bundling or splitting of shipments in the PI. **Interviewee II, Interviewee IV, and Interviewee VII** mentioned a similarity regarding the splitting of packets and states how when one sends something over the Internet, it is split into small packets, and in the PI, the same process is supposed to happen with shipments. **Interviewee VII** also describes how messages in the DI are split up into packets via a TCP/IP protocol. **Interviewee IX** describes the same process and adds that information on the DI can be split in data packets and these are routed in different ways over the Internet via the path of least resistance and assembled at the side of the receiver. I**nterviewee III** describes how packets move over the DI similar to how containers move over the PI. In addition to splitting **Interviewee III** also states that packets may be bundled before they travel over a link, which he refers to as multiplexing. **Interviewee I** also describes this technology and compares container ships to deep-sea cables. He describes how smaller packets are all packed together and sent via a cable as one larger packet, similar to how containers are stacked on a containers ship Both **Interviewee V** and **Interviewee IX** stated that splitting may also happen in the PI, but not in an exactly similar way because physical packages cannot be duplicated when lost.

Organization

Four interviewees describe similarities in the organization between the DI and the PI. **Interviewee XIV** elaborates on the decentralized organization of both domains where the decision power of routing recites in a DI router of a logistics hub, and it is not the forwarder or the shipper that decides upon the whole logistics chain. **Interviewee VI** approaches the analogy by describing that both domains have a network of networks where networks are linked and which is accessible to everyone by the use of standards and protocols. **Interviewee V** drew an analogy on a structural level by referring to how the networks are organized and how Logistics Service Providers can be compared to Internet Service Providers. **Interviewee XIII** gave a detailed explanation on the packet switching technology in the DI and compared this to cross-docking operations in the PI.

Standardization

The most frequently mentioned similarity between the DI and the PI is standardization. **Interviewee II, Interviewee IX, Interviewee XV, Interviewee XIV, Interviewee XII, Interviewee VIII,** and **Interviewee VI** describe how the PI has a standard set of rules to transport a container and compare these to protocols in the DI. **Interviewee IX** and **Interviewee XV** also refer to the maritime containers as an example for a standard in the PI. **Interviewee XIII** likewise recognized the need for protocols in the PI and the DI. He describes that in the DI, there are thousands of protocols, but the main protocols that are used for managing the flow of traffic are specified by the routing manufacturers. He explains that similar to the PI; it does not matter what goes on inside a router of a physical hub; what matters is what goes on at the boundaries, meaning that inbound traffic is handled uniformly and that outbound traffic is handled uniformly with outer routers and that this is generally managed in the TCP/IP protocol.

Automation

Five interviewees described similarities from an automation perspective. **Interviewee XI** talked about automation as the most appealing part of the PI analogy and envisioned the PI to be like the DI: fully automated, and users can send their shipments by the push of a single button. **Interviewee VII** explained that sending a shipment over the PI should be like sending an e-mail, and the shipment should arrive at the destination automatically. **Interviewee VI** and **Interviewee III** also recognize that transshipment in the PI should be automated, so there is no human intervention in transporting goods from A to B. **Interviewee XV** acknowledged there may be some similarities between the DI and the PI in terms of routing and the objective function of a routing protocol. He assumes the basic methodology behind it is quite similar. However, there may be differences in the aim of optimization, he acknowledges. *"In the PI, we will aim to optimize transportation in different ways and will avoid losing packets, as one cannot duplicate them, which will be different in the DI,"* he explained.

Openness

Three interviewees described how the PI should have an open character like in the DI where everyone who complies to a specific set of rules would have access to the network via a service provider, which makes the threshold to use the system low. One interviewee also described how PI actors could use each other's networks and assets similar to what happens in the DI. **Interviewee XV** gave the shared use of the Atlantic Ocean Internet cables as an example of asset sharing.

User Experience

Five interviewees mentioned user experience as a similarity. With this, they referred to the ease of joining and using the network. Two interviewees related the carefree user experience of sending an e-mail over the DI to sending a container of the PI. Three Interviewees compared the trust users have in the DI to the trust users will have in the PI.

Flexibility

The final similarity that was referred to is the flexibility the DI and PI offer in terms of routing. Two interviewees mentioned that traffic on the DI can easily and automatically be rerouted when necessary and envision the PI to offer similar flexibility.

4.2. Perceived Differences

We summarize the difference mentioned by interviewees in Table 3. Again, we cluster these differences based on whether they are on the attribute level or on the relational level.

Table 3. PI experts perceived differences between DI and PI

Level	Code Group	Mentioned by
Attribute	Differences between packet and packages	II
	Differences between DI and PI in evolution	II, IX, XI, XII
Relational	Differences in speed & use of modes	I, III, V, XV
	Differences in splitting and bundling shipments	I, IV, VII, IX, X, XI, XIV
	Differences in costs	VI, XIV
	Differences in replication and duplication options	I, V, IX, X, XI
	Differences in planning and decision making	I, II, III, IV, V, IX, X, XI, XII, XIV, XV
	Differences between packet and packages	I, III, V, XIV
	Differences between DI and PI in evolution	II

Attribute Level

Five interviewees drew differences between attributes in the DI and the PI. One of the interviewees mentioned differences in the number of major providers for the DI. A further four interviewees described differences between the structure of packets in the DI and packages in the PI. In this, they refer to the heterogeneity (size, weight) of physical packages compared to standardized DI packets.

DI and PI Evolution

Four interviewees describe how the DI evolved differently from the PI. Interviewee XV and Interviewee I describe how the development of the DI was driven by the desire to exchange information, starting out in an academic setting. Interviewee I also elaborates on the collaborative aspects of the DI and compares this to the PI domain, where actors own their own assets, and there is limited collaboration. Interviewee V points out how the DI and the PI developed differently, which resulted in the PI being fragmented with a large number of actors, whereas the actors in the DI used to be monopolies in the beginning, leading to a seemingly unified market.

Speed and Modes

Six interviewees mentioned differences in the transmission speeds in the DI and the PI. They explain how in the DI, information moves with instantaneous, only limited by the speed of light, while in the PI the movement of shipments takes longer. Likewise, three interviewees refer to transit times in the PI, which are not comparable to the DI. **Interviewee XIV** also recognizes the difference in magnitude regarding time; however, he emphasizes that in the DI transportation is not instant and that there is still a transfer time, but instead of two days, it may be two milliseconds. Related to the difference in speed is the difference in the usage of modalities, which two interviewees describe. According to them, in the PI there will always be different transport modalities and that logistics hubs should be able to handle different transport modalities, where this is not the case in the DI. Likewise, one interviewee described how information in the DI could be sent instantaneously, while shipments in the PI have to wait for a modality to be transported.

Splitting and Bundling Shipments

The splitting and bundling of packets in the DI and packages in the PI have been described as a similarity as well as a difference. Two interviewees described a difference in how and why bundles of cargo can be made in the physical world as opposed to the DI. Both interviewees recognize there are advantages of bundling cargo for transport in the PI, whereas in the DI, one large piece of information may be split up into smaller pieces, but these pieces are not joined together for transport as in the PI.

Costs

Five interviewees describe differences in cost structures between the DI and the PI. **Interviewee V** and **Interviewee XI** described the difference in marginal transportation costs. The interviewee stated that in the DI, the marginal costs are close to zero and explains that all equipment and infrastructure are financed as an investment, after which the cost of sending a packet is close to zero. In the PI, however, there are always going to be marginal costs such as loading costs and fuel costs. **Interviewee X** also described the low costs of transferring digital information and explained that the revenues from the DI are not coming from operating a single byte of digital information, and the costs for users are usually based on a flat rate of a certain bandwidth. **Interviewee I** made the distinction between public financing of the infrastructure in the PI and the financing of infrastructure in the DI.

Replication and Duplication Process

Interviewee IX describe how there is a difference is cost of duplication information in the DI and duplication physical goods on the PI. Here he referred to data packets getting destroyed and remade in the DI, which cannot easily be done in the PI. As for the latter eleven interviewees mentioned the difference in the duplication and replication possibilities on the packets in the DI and packages in the PI. They described how packets can be lost or destroyed in the DI, due to congested links, unavailable hosts and an expired time-to-live of data packets. In this case a data packet can be generated again, while in the physical world, a physical package cannot be regenerated in the same way.

Planning and Decision Making

Interviewee I explained how, in order for the PI to work, one may need a type of planning before sending a shipment into the network and communicate to hubs in the network that a shipment is coming because one needs space and infrastructure to store the physical goods. **Interviewee V** described how in the DI a packet could be sent without knowing if there is a route available to the destination. Similarly, **Interviewee XIV** makes the argument that the sooner you know what shipments are sent, the better the chances are to efficiently bundle shipments to move over the network, which is not necessary in the DI.

4.3. Misconceptions of the Digital Internet

In this subsection, we will discuss inaccuracies in the mental models described above, and how they inflict on the DI/PI analogy. For this purpose, we will select three cases, which highlight common strains of misconceptions.

Packet Routing, Aggregation, and Modes

When it comes to the way the DI works in terms of packet routing and aggregation, we find that the perceptions of our interviewees are often influenced by common analogies for *explaining* the DI, borrowed from the physical world, for example, ironically logistics. The main point here is often the omission of layers involved in common activities on the DI. For example, emails are seen as a discrete activity. However, this only relates to one layer, the application layer, of what is involved in sending an email. The, also regularly mentioned, ‘splitting’ of packets, i.e., in this case splitting of one email into several network packets, is transparent to the systems handling the email, and rooted in the fact that data in itself is not discrete (depending on the layer), much unlike physical goods being transported (Braden 1989).

Furthermore, perspectives on routing that assume that individual parts, i.e., packets, of a connection between two systems (over which, then, an email might be transported) may travers the Internet via different routes is inaccurate. Instead, routers hold a routing table, which outlines the next hops for packets to a certain destination. Unless the routing table changes, all packets will flow via this path. This, however, does not entail that answers to these packets traverse the same path; Routing on the DI is not necessarily symmetric. If, however, the routing table does change during one connection, this is not an issue, as most network protocols are resilient against reordering. This ties in with the misconception that DI packets are regularly reordered. This is something that *may* happen, not the default case, and usually connected with significant performance degradation, as the receiving site has to wait until all missing packets have arrived (Postel 1981).

Furthermore, when we look at *modes* on the DI, we indeed find countless. There are wireless connections, cooper cables, DSL and other broadband techniques, and fiber-optic connections. What allows systems to communicate over these different modes transparently is the use of standardized higher-level communication protocols. In fact, this is not much different from ISO containers being used to allow a seamless switch between, e.g., ships and trains. See, for example, how this is handled for WiFi (Gast 2005).

Protocols, Organization, and Standardization

Another common disconnect we found revolves around standardization. Specifically, we found that the concept of how standardization of protocols takes place in the DI is driven by an industry heavy perspective, e.g., **Interviewee XIII**, who described router manufacturers as the driving force behind routing algorithms. However, protocol standardization on the Internet, is an open and community driven process, in which, of course, manufacturers take part. For a comprehensive overview of protocol standardization procedures, we recommend taking a look at the procedures of the Internet Engineering Task Force (IETF), the defacto main standardization body for Internet Protocols, which publishes the Request For Comments (RFC) series (Bradner 2003, Russel 2006).

Costs and Planning

Two common themes in the context of the DI are the impact of costs and planning. Several interviewees mentioned that the impact of operational costs is limited in the DI, and instead infrastructure mostly incurs capital expenses. They see this as a significant barrier to the usefulness of the DI/PI analogy. However, in practice, capital expenses are only a minor part of operating a network. Instead, a network operator incurs significant costs from staff, power, space, and maintenance needs of network infrastructure (Gruber 2009).

This point ties in tightly with a perception that capacity planning and coordination are not a concern in the DI. However, a major task of network operators in the DI is indeed capacity planning (Feamster et al. 2001). While it is true that *end users* do not have to consider their network provider's capacity, in larger networks traffic engineering to accommodate capacity needs is a fundamental task to ensure the network continues to function. A common case where this can be seen is the handling of flash-crowd events, e.g., during large software releases (Blendin et al. 2018).

5. Discussion

Looking back at our interviews, we find that PI researchers are aware of inherent differences between the DI and PI. However, at the same time, their understanding of similarities is often abstract and on an aggregate level. For example, four interviewees mentioned the convenient user experience that is currently offered by the DI and soon offered by the PI. Although the interviewees explain the convenience is a result of automation, they could not elaborate on which processes in the DI are automated, how they are automated, and how that is similar to the PI. Similarly, reflections on technical aspects necessary to draw design recommendations from the DI are limited, most commonly in the context of routing and packet handling. We find that, in many cases, interviewees made assumptions about particular technologies. Still, they found it challenging to elaborate on their assumptions. Hence, we conjecture that our participants' mental models are often influenced by their understanding of the DI. Ironically, analogies from logistics, e.g., in the case of email and the handling of senders and receivers, may have created those mental models in the first place, which are now transferred back within the DI/PI analogy.

5.1. Functional Properties of the DI/PI Analogy

Given our observations, we can now assess the DI/PI analogy in terms of their functional properties against the AFM, see Section 2.

Persuasion

The DI/PI analogy is clearly useful for persuasion purposes. As one of our interviewees explains, the analogy between the DI and the PI helps people open up their minds and think about a whole new logistics paradigm. The interviewee explains that there are many inefficiencies in our current logistics operations due to various bottlenecks. The analogy makes people realize that logistics can be a lot more efficient. Using the DI/PI analogy, people can see that it is possible to change a paradigm completely. Obviously, the DI/PI analogy has proved to be effective in persuading both researchers and practitioners to further explore the topic.

The limitations in the strength of the analogy, as well as the limitations we observed in researchers' understanding of the source case, i.e., the DI, do not pose a major issue, as the subject of persuasion is not directly tied to the accuracy of the analysis: Researchers should be persuaded to open their mind and thing out-of-the (logistics) box, instead of implementing aspects of the DI in the PI.

Explanation

Although the DI/PI analogy may initially not be meant for explanatory purposes, we also find it being used and useful for explanatory purposes. In fact, we find that some of the inaccuracies we observe in researchers' understanding of the DI may stem from logistics networks originally having been used (sending packages/packets, information highway) for explanatory purposes to elaborate on the DI to a non-IT related audience. Similarly, disconnected from technical specifics, one of our interviewees noted that they use the PI as an idea of a future and advanced state of the logistics network: *"We use the DI to explain what this advanced state of logistics looks like."* A further two participants mentioned that they use the analogy to explain different logistics paradigms. While one has to be careful in using analogies for explanatory purposes—another interviewee mentions one should be careful when lecturing about the PI, as students may not have a proper understanding of the DI—the goal of using the DI/PI analogy to logistics concepts is on *understanding* the logistics concepts. Hence, inaccuracies are not an issue, as long as the explanatory goal is correctly reached.

Inspiration

The origin of the DI/PI analogy is its use for inspirational purposes, most likely starting with the Economist's cover in 2006, whereas later many foundations of the PI were inspired by the DI, such as the interconnection and real-time synchronization of networks, development of standards and protocols, and creating heterogeneous certified equipment that is respecting a certain protocol (Montreuil 2011). However, it remains difficult to find out which foundations are inspired by the DI as opposed to which had already been part of the logistics agenda for years. Several of our interviewees note that the analogy best fits on an inspirational level. The similarities they described are often generic and similar to high level design requirements. When the interviewees talk about the similarities, they normatively elaborate on what the PI should do or become. For example, many interviewees mentioned that the PI should be flexible, automated, and easy to use. In their argument, they refer to the DI, which, according to them, complies with these requirements. Another example is that interviewees mentioned that they aspire to have full automation in the PI just as in the DI. These are examples of design requirements that are *inspired* by the source case of the DI. As, again, the technical ground-truth of DI aspects used for inspiration is not crucial, but instead the mental model researchers have of the DI—accurate or not—we find the strength of the analogy to be sufficient to inspire new developments in logistics.

Design

We find that the point where the DI/PI analogy breaks, see Figure 3, is the design function. While our interviewees were generally able to express technical aspects in aggregate and high-level terms, the analogical structure, and prior use of logistics analogies for explanatory purposes to explain the DI lead to inaccurate descriptions of the DI's technical foundations. Fundamental differences, as for example, the ability to perform zero-cost copies of data, limit the applicability of the DI as a design template for PI technologies. An example of this breaking point is the use of caching in the DI, commonly implemented by Content Delivery Networks (CDNs). When a user requests a resource, for example, a picture, for a web-page, the CDN will copy that picture to a CDN node close to the user. If then another user topologically close to the first requester requests the same picture, that request can be directly served from the cache of the node close to the user, without requiring the CDN node to retrieve a copy from a central place. Transferring this concept to the PI is technically not possible, as goods cannot

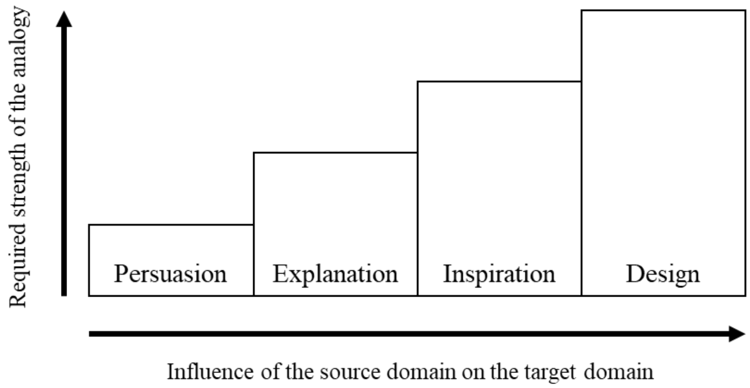

Figure 3. Breaking point of the DI/PI analogy in the AMF

be easily recreated from a single copy in-place. Instead, the use of the analogy should be downgraded to a more inspirational purpose, which does not strive to design PI elements directly aligned with the DI template.

The design of PI technology should, therefore, not be dominated by 'how is this done in the DI' but instead by 'how can we reach this (perceived) property of the DI we would like to attain'. To illustrate this in example, the question should not be 'How can we aggregate shipments as effectively as in the DI?', but instead 'How can we aggregate shipments to utilize logistics capacity more efficiently?'. While the first question implies that the DI may serve as a design template, it is also inaccurate insofar that there is no packet aggregation. The second question, while highly similar, acknowledges a need, which—as perceived by researchers—has been solved in the DI case by using aggregation. Leaving out the technical perspective of the DI then decouples the question from potential inaccuracies and personal beliefs and leads to a productive direction to improve logistics.

5.2. Limitations

Like all scientific research, our study has several limitations which have to be mentioned to contextualize our results and to allow further improvement of the work in future studies. In our study, we focus on academic researchers (working in industry and universities), familiar with the PI concept, as the main innovation drivers for the PI. This means that our approach may exclude more practical design driven perspectives from implementers and users of PI technology. Furthermore, due to the chosen research paradigm, i.e., a qualitative study on mental models of the DI/PI analogy, we cannot provide a quantitative perspective on the events and effects we describe. However, with the purpose of our study being explorative, and our sample containing a major portion of researchers currently active in the PI community, see Section 3.3, we still provide a perspective on the belief state of this subfield of modern logistics.

6. Conclusion

In our study, we conduct 15 semi-structured expert interviews and find that the sourcing of concepts from the DI is regularly driven by researchers own mental models, which diverge from the actual concepts in the DI. Following our Analytical Functionality Model (AFM) rooted in literature, we find that the analogy's strength is limited by fundamentally diverging realities in some aspects between the DI and the PI. Hence, we argue that the use of the DI/PI analogy should be focused on argumentative, illustrative, and inspirational purposes, and only be applied for design purposes with reserve. The AFM confirms that the analogy still fulfils important functions: to introduce new members to the topic, to facilitate a systematic description of the key PI concepts and to reach convergence between community members in their directions of thinking about future logistics systems.

To the PI research community, we recommend that it acknowledges the disconnect from the technical foundations in the DI for the PI, and refrains from using the DI as a design template for PI technology. While useful to discuss key PI concepts, the PI should also emancipate itself from its explanatory and inspirational roots and develop its own design narrative. Secondly, we also recommend that future research looks further into the use of analogical reasoning for innovation communities. The DI/PI analogy has shown to be a very powerful tool to build up a community of dedicated researchers and practitioners. Opportunities to build on our work with new research include the use of quantitative models and the closer involvement of actors implementing and using PI technology.

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Appendix A – Interview Script

Pre-Interview Script

I would like to thank you once again for being willing to participate in this interview as part of my research. As I have mentioned to you before, my study seeks to understand the analogy between the digital internet and the physical internet and how the workings of the digital internet are perceived. I want to ask you about your knowledge and thoughts about the analogy between the physical internet and the digital internet. I will first ask you about what you think the analogy entails. After which, I will ask you about specific components from the physical internet and how you think the technology works in the digital internet. Please try to be as elaborate as possible and try to support your answers with graphic descriptions when you can. Our interview today will last approximately 40 minutes.

1) Do you have any questions?
   a) [If yes]: [Discuss questions]
2) Before we start off, have you been able to look at the consent form yet?
   a) [If yes]: Thank you, was everything clear or do you still have further questions?
   b) [If no]: [Discuss questions]
   c) [If the interviewee has not looked at the consent from yet]: [present the consent form again]
3) The consent form indicates that I ask your permission to audio record our conversation. Are you still ok with me recording (or not) our conversation today?
   a) [If yes]: Thank you, please let me know if at any point you want me to turn off the recorder
   b) [If no]: Thank you for letting me know. I will only take notes of our conversation.
4) Before we begin the interview, do you have any questions?
   a) [If yes]: [Discuss questions]

Pre-Interview Script

[start the recorder and announce that the interview has started]

1) How are you connected to the physical Internet [research]?
2) How would you define the physical Internet?
3) What does, according to your knowledge, the analogy between the physical Internet and the digital Internet entail?
4) Do you think there is an analogy on interconnectivity between networks?
   a) [If yes]: Can you describe how this technology works in the DI?
5) Do you think there is an analogy on standardization?
   a) [If yes]: Can you describe how this technology works in the DI?
6) Do you think there is an analogy on protocols?
   a) [If yes]: Can you describe how this technology works in the DI?
7) Do you think there is an analogy on encapsulation or modularization?
   a) [If yes]: Can you describe how this technology works in the DI?
8) Besides the answers on these questions, would you like to add anything else to your answer at question one: What does, according to your knowledge, the analogy between the physical Internet and the digital Internet entail?

Thank you for your answers, we will now end with some general questions.

1) What is your profession?
2) What is your field of expertise?
3) How many years have you been active in this field?

Thank you for your participation in this study.
[stop recording]