PI Containers: Assessment of Functions and Development from an Engineering Design Related Perspective

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Abstract:

The idea of containerizing goods is a central component of the Physical Internet philosophy, as this containerization serves to abstract and standardize goods and shipments. This approach promises to simplify the handling of shipments on the one hand and deliver shipments more efficiently throughout the transport network.

In the present work, scientific publications were evaluated according to the terms Physical Internet, PI Container and containerization. Out of almost 300 examined scientific publications, more than 25 could be identified that had a strong focus on the topics of PI Containers and containerization. These identified articles were methodically compared by categorizing them according to aspects highlighting the technical view on the current state of development of PI containers.

Our research shows that over the past 12 years, just a few cases were documented where specific engineering design solutions of a PI container were presented and tested in real-life applications. Thus, we conclude that further research into the technical design of PI Containers is needed to identify use cases where the deployment of PI Containers has a significant positive impact, is accepted by users, and is accessible under economic, ecological, and technical aspects.

Keywords: *Containerization, Physical Internet, Physical Internet Container, Transportation, modularization*

Conference Topic(s): *interconnected freight transport; material handling; Modularization; PI fundamentals and constituents; PI impacts; PI implementation; vehicles and transshipment technologies.*

Physical Internet Roadmap *(Link): Select the most relevant area for your paper: ☐ PI Nodes, ☒ PI Networks, ☒ System of Logistics Networks, ☒ Access and Adoption, ☐ Governance.*

1 Introduction

The idea of containerizing goods is a central component of the Physical Internet philosophy, as this containerization serves as a tool to standardize goods and shipments. This approach promises to simplify the handling of freight on the one hand and to deliver shipments more efficiently throughout the transport network on the other. (Montreuil, 2011)

Therefore, it is unavoidable that, in future scenarios, special PI Containers need to be developed and used within the PI network. In the past, PI Containers appeared in many publications and had many shapes and forms in different scientific works. However, most of these studies had one thing in common: they generally assume that the boxes already exist in real life. The actual scientific investigations, however, are mostly virtual, that is, simulation-based. In these publications, the PI Containers served as a model for simulation or even exist just as a mathematical model or in visualization. Except for fewer exceptions, such as the MODULUSHCA project, where a PI Container was designed, built and tested in real-life scenarios. Most of the research on PI container behaviour has been conducted virtually, using mathematical models on a simulation basis since the introduction of the Physical Internet Idea in 2011.

The MODULUSHCA project seems to be one of few works and scientific publications that let the PI Container leave the virtual world. (Landschützer et al., 2015) Designing, building and testing a real-life PI Container bring new challenges that must be considered. Physical properties, such as mass and the volume of the PI Container, the strength of the material, as well as costs, ecological benefits and operational factors, e.g. the complex functions and the usability, may not be crucial aspects for simulation studies according to routing or packing problems. Still, for real-life PI Containers, going through transport networks, they are and will be decisive for whether PI Containers can sustain in real-life scenarios and transport networks..

As containerization is one of the crucial pillars of the Physical Internet, this paper will address the evolution of PI Containers from the very beginning of the Physical Internet Philosophy in 2011 to the present, from an engineering design-related perspective, including the analysis of how the design of PI Containers has evolved. The other aspect of this paper will be to show the number of projects and papers dealing with the practical application and introduction of PI Containers (or separate functions) to the logistics network.

Therefore over 300 PI-related publications, papers or projects were analyzed and evaluated following a Systematic Literature Review. The research questions discussed within this paper will be elaborated on and explained in the methodical part (see section 3.1). However, this work will focus on the overarching question:

- According to an Engineering Design Related Perspective, how physical is the Physical Internet Container?

2 Methodology

A Systematic Literature Review (SLR) applied in that paper allows the summary and process of information and the literature on a specific topic, in this case, PI Container. Therefore in the first step, all relevant information and literature need to be collected and reviewed. The aim is to screen the applicable literature for relevance according to the research questions. Therefore, the literature review focused on Papers and Publications which address the topic of Physical Internet Containers. Further, to gain information on the evolution of the Physical Internet

Containers, the most relevant publications were analyzed and categorized considering different aspects. According to the schema and the workflow of this method of Systematic Literature Review, the following steps were processed (Xiao et al., 2017):

- Problem Statement/problem Formulation
  Objective: Clarification of the Research Question
- Development of the review protocol
  Objective: Setup of explicit inclusion/exclusion criteria
- Data acquisition
  Objective: Search of relevant Literature → Review title
- Data screening
  Objective: Screen for inclusion → Review Abstract
- Data quality
  Objective: Assess Quality → Review Full-text
- Data Extraction
  Objective: Validate and categorize data
- Analysis and Syntheses
  Objective: Findings of the Literature Review, Answer the Research Question

Chapter 3 shows the application of those steps SLR steps on the current research topic.

3 Systematic Literature Review – Method application

In chapter 2 the method of the Systematic Literature Review was described. This chapter will show the application of this method, including all process steps of the method on the present research question. All process steps, beginning with the setting of the research question, will be applied and described separately in the following section 3.1 to 3.6

3.1 Problem Statement

The aim of this paper is to show *the development of PI Containers over the last years as well as the technology readiness of specific solutions*. Therefore this literature review focuses on PI-related work which directly or indirectly addresses the topic of PI Container to answer the following research questions:

- RQ 1: How many works addressed the PI Container as a primary topic (including development over the last years)
- RQ 2: What's the degree of abstraction of the PI Container treated in the different works
- RQ 3: To what extent are physical aspects included in the design of the PI Container

3.2 Development of the review protocol

The International Physical Internet Conference (IPIC) proceedings were defined as the primary source for publications. Therefore all proceedings from IPIC 2014 to IPIC 2021[1] were described as a source of relevant literature.
As a second source of potential literature, all works which cited the MODULUSHCA project publications were also included in the pool of potentially relevant publications.
In addition, further popular search engines for scientific work (Google Scholar, ResearchGate and Scopus) were used to find other publications dealing with the Physical Internet, specifically

[1] In year 2022 IPIC 2022 was not held due to the global COVID19 pandemic situation

with the sub-topic of Physical Internet Containers. Therefore, the following keywords were defined:

"Physical Internet" or "PI" or "π"

and

"Container" or "Containerization/Containerization"

Further, it was defined that the process steps of *data acquisition (Review title)* and *data screening (Review Abstract)* will be applied simultaneously.

3.3 Data acquisition

As a first step, all potentially relevant papers and publications are listed. According to the review protocol, the major part of this accumulation was formed by contributions of IPIC (International Physical Internet Conference) as well as from publications which cited the MODULUSHCA project publications, in sum: 265. In addition, a minor number of publications and papers were collected via standard search engines for scientific works, in sum 32 (as described in section 3.2).
This list of publications and papers includes *almost 300 positions*. These publications were validated roughly by reviewing the works' titles and abstracts as a next step. This review aimed to sort out all publications which probably do not address the topic of PI Containers in a significant matter. Therefore, papers addressing the issue of Physical internet Containers or containerization of goods within the title or the abstract will be considered further. This adjusted list includes *25 potential publications* and serves as a base for further investigations in process step *data quality* (see section 3.4)

3.4 Data quality

The first rough review of the potential publications (see section 3.3) showed that *25 publications* potentially significantly address the topic of PI Container. In the next step, the publications were reviewed in detail to determine in which depth they focus on PI Container. To reduce the number of relevant papers again, all papers whose content does not show the relation to PI Container or interpret the PI Container differently than the PI Philosophy mentions get struck from the list of relevant publications. Therefore it has been defined that the mentions of the Physical Internet Container within the Container must exceed the references of the Physical Internet fundamental research publications (Montreuil, 2011) to take this publication under further consideration. This process step is shown in Table 1.

Table 1: List of relevant publications after data acquisition

Source	PI Container as significant content	Comment
Montreuil et al. (2014)	✓	Introduction and development of the concept of Pi Container
Pach et al. (2014)	✓	PI Container as a Hexader for packaging simulations
Walha et al. (2014)	✓	PI Container with different dimensions, mathematical model
Tran-Dang et al (2015)	✓	PI Container with different dimensions for packaging simulations
Tretola et al. (2015)	×	Definition of Data Sets based on MODULUSHCA
Landschützer et al. (2015)	✓	Specific design and prototype of PI Container for field testing

Chakrouun et al. (2016)	×	General description of PI Container
Kapplmüller at al (2016)	✓	Specific design of a PI Container incl. specific dimensions and functions
Hao et al. (2016)	✓	General description of PI Container, function of PI Container in PI Hub
Salley et al. (2016)	×	General description of PI Container, focus on information exchange
Faugere et al. (2017)	✓	Description of dimensions and functions
Di Febbraro et al (2017)	✓	Mathematical Modell of PI Container incl, different dimensions
Krommenacker et al (2017)	×	General description of PI Container
Tran-Dang (2017)	✓	Description of functions of PI Containers, several simulations
Chargui et al. (2018)	✓	General description of PI Container, function of PI Container in PI Hub
Buckley et al. (2018)	✓	PI Container with different dimensions, mathematical model
CLUSTERS 2.0 (2018)	✓	Detailed description of requirements for New Modular Load Units
Marino et al. (2019)	×	General description of PI Container
Bennekrouf (2019)	✓	PI Container with different dimensions for packaging simulations
Sternberg et al. (2020)	✓	General description of PI Container, packaging simulations
García-Arca et al. (2020)	×	Redesign of cardboard boxes, low relevance for PI
Tran-Dang et al. (2021)	×	General description of PI Container
Hayek et al. (2022)	✓	Development of PI Container for wood transports

Within this process step, the list of relevant publications could be reduced again and led to a final list of *16* publications which will be used for a more in-depth analysis of the contents in the next step (see section 3.5).

3.5 Data Extraction

As a next step, all relevant publications were reviewed and analyzed according to their applicability to the research questions to answer the two questions defined below (see chapter 1)

- RQ2: What's the degree of abstraction of the PI Container treated in the different works
- RQ3: To what extent are physical aspects included in the design of the PI Container

All relevant publications were categorized within the following chart, shown in

Figure *1*. Therefore two different aspects were introduced to be able to validate the various publications and place them in the chart

- The Technology Readiness Level (TRL) indicates how advanced the solutions mentioned in the publications can be seen according to their stage of development (Mankins, 1995). Therefore the scale reaches from TRL 1 (Basic Technology Research) over TRL 3 (Experimental proof of concept) and TRL 5 (Technology validated in relevant environment) to TRL 9 (Prototype in field tests)
- The scale of the relevance of physical aspects and functionality shows how the physical parameters (weight and volume of the Container, strengths of the material[2]) and functionalities were considered for the specific solutions. In order to be able to categorize the state of design of the PI Container within the publications from a design-

[2] This paper focusses on the investagtion of the physical and mechanical properties of Physical Internet Containers (such as mentioned above) therefor the relevant parameters are weight, volume and strength of the material are taken under consideration for further research. Ecological as well as economical parameters will not included in the research within this paper.

related perspective, the method of *Planning and Design Process* is used to classify the mentioned PI Containers into the following stages within that *Planning and Design Process* (Pahl, Beitz, 1996):

- Planning and clarify
- Conceptual design
- Embodiment design
- Detail design

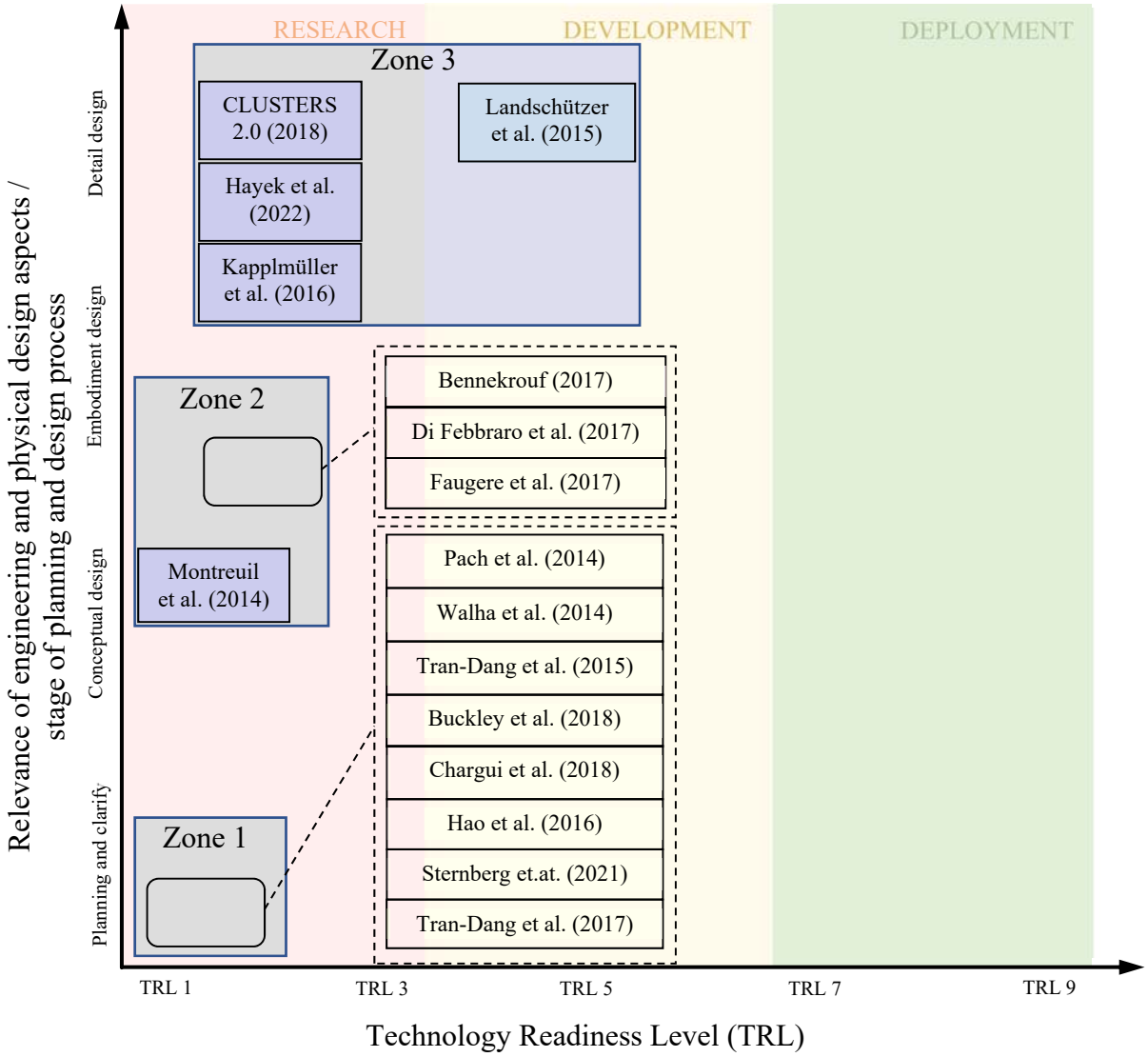

Figure 1: Classification of relevant publications

Further, the relevant papers can also be categorized and sorted according to their year of publication, which allows answering the research question, defined in chapter 1

- RQ1: How many works addressed the PI Container as a primary topic in the past (including development over the last years)

Table 2 shows the categorization of the most relevant papers indicating the development and the degree of scientific investigation on PI Container, represented by the number of mentions of PI Containers within scientific publications over the past years. Therefore, the last row in the table represents the total amount of relevant publications published each year.

Table 2: Evaluation of the development of relevant publications from 2014 to 2022.

2014	2015	2016	2017	2018	2019	2020	2021	2022
Montreuil et al.	Landschützer et al.	Hao et al	Tran-Dang	Buckley et al		Sternberg et al.	Tran-Dang et al	Hayek et al.(2022)
Walha et al	Tran-Dang et al	Kapplmüller at al	Di Febbraro et al	Chargui et al				
Pach et al.			Faugere et al					
3	**2**	**2**	**3**	**2**	**0**	**1**	**1**	**0**

3.6 Analysis and Syntheses

The result of the processed Systematic Literature Review can be summed up within the following *quantitive takeaway*

- Out of almost *300 papers* and scientific works addressing Physical Internet and Physical Internet Containers, *25 publications* address PI Container directly or indirectly (see section 3.3)
- Out of these *25 publications* addressing PI Container direct or indirect, no specific or unique statements or new findings according to PI Container could be made within *12 papers* (see section 3.4)
- The remaining *16 publications* were analyzed according to their quality. (see section 3.5) This analysis focussed on the development the number of mentions of PI Containers within the last years on the one hand and the approaches and solutions of PI Containers within the publications on the other.

The *qualitative takeaway,* however, will be summed up and analyzed in chapter 4 - Results.

4 Results

After processing the steps of SLR, from data acquisition to data extraction, it can be seen that the investigated publications, which deal with the PI Container in a physical matter, share similar characteristics:

- The Technologie Readiness Level (TRL) reaches a maximum of TRL 4 within one investigated publication. All other solutions or approaches of PI Containers in the other publications show lower TRL, most of them TRL 1. No projects or publications address the goal of introducing Ready-to-Use solutions (up to TRL 9) to the market, as shown in Figure 1 by the missing publications in the deployment sector.
- A few investigated publications and projects address integrating physical aspects and parameters into their solution and approach to the PI Container. This is shown by classifying the publications to the stage within the *Planning and Design Process*. A few solutions exceeded the stage of developing ideas, meaning most of the investigated publications are stuck at the stage of description and formulation of the essential functions of the PI Container without including further design steps.
- The MODULUSHCA project (Landschützer et al., 2015) is the only publication which combines a thoughtful design (including physical aspects) with and higher technology readiness level (TRL 4). However, since then, no publication has considered forward pushing of projects comparable to the MODULUSHCA project. The project CLUSTERS 2.0, which can be seen as a Follow-up project of MODULUSHCA, does catch up on the relevance of the physical properties and functions of PI containers. However, the New Modular Logistics Units (NMLU) development did not exceed the design phase and did not lead to a prototype within that project. Further, one publication

shows the detailed development of a PI Container for wood transportation (Hayek et al. 2022). Still, this publication holds a low TRL level, but it mentions the importance of introducing such solutions to the transport network.
- the SLR has shown that the number of publications dealing with PI containers as physical containers have increased in recent years.
- Further, the focus on developing Physical Internet containers has decreased over the last years. This can be underlined by a combined view of Figure 1 and Table 2, which shows that nearly all solutions and approaches of PI Papers published since 2017 need to be classified as low stage within the *Planning and Design Process* as well as TRL 1.

Although the PI Container is one of the main pillars of PI philosophy, just a few scientific publications focus on matching PI Containers for real-world application by developing, designing, building and testing PI Containers in real-life scenarios.

5 Conclusion and Outlook

The structured analysis and evaluation showed that in the research landscape, the PI Container still seems to be seen as an object in the virtual world. Further, it could be seen that the philosophy of PI assumes to a certain extent that the PI Container must exist to fulfil the tasks and objectives of the Physical Internet and to be able to apply the Physical Internet to the future transport network. However, there is less effort to develop a physical Physical Internet Container. Even the step seen in the past years creating a physical PI Container decreased in quality and intensity. Since MODULUSCA prototypes of a modular PI Container were developed, designed, built and tested, the PI Container seemed to be more virtual daily from then on. This means there is a research gap after the MODULUSHCA, shown in this paper. This gap covers the need for a physical PI Container to help the PI succeed on the one hand, as well as decreasing the effort to design and introduce such PI Container.
Further, the transport network has undergone many changes and new challenges over the last years (e.g. the increasing number of Polybags, limited transport capacities, and legal restrictions for transportation and delivery). That results in a low level of acceptance for introducing PI Container to the existing transport network. That aspect underlines the need for new approaches and design suggestions to find possible cases within the transport network where the introduction of PI Container would lead to an ecological or economic benefit and design and test PI Containers for that application.
For that reason, there will be follow-up research which will catch up on the findings of this paper and try to find some new cases or scenarios where the introduction of PI Container could help to push the Physical Internet Idea. Potential objectives for such future research efforts could be

- The definition and description of specific Use Cases within the PI network, with high potential that the usage of PI Boxes can result in an increase of efficiency regarding handling, including all physical aspects of a potential physical PI Container
- Methodical design of a PI Container which can fulfil the requirements of the Use Case, defined before, including prototypical implementation
- Definition of conditions and processing of a field test of the designed PI Container

6 Acknowledgements

Parts of this work received funding by the Austrian Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology (BMK) in the research program "Mobilität der Zukunft" under grant number 877710 (PhysICAL).

The authors of this paper received particular support from Maximilian Steger by giving input from his expertise on PI Containers and giving editorial support.

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