PHYSICAL INTERNET: A REVIEW OF MATHEMATICAL PROGRAMMING MODELS

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ABSTRACT

The development of digital technology has facilitated the growth of e-commerce and the recent pandemic has changed the purchasing process and strongly impacted supply chains. These must adapt in order to keep their performance level. As a response to this challenge, the concept of the Physical Internet, which is based on the Digital Internet, looks promising. Hence, we can take advantage of advances in information technology to develop the Physical Internet and to accelerate its implementation. In this paper, we propose a review of the Physical Internet literature based on mathematical programming to answer the following questions: (1) what is the coverage of nodes and links in a supply chain by the current literature on the Physical Internet? (2) What mathematical programming models and formulations are used for modeling and optimizing the problems of supply chains in the context of the Physical Internet? (3) How are sustainability aspects addressed by the proposed models? Following the qualitative content analysis method, we worked in detail on 60 publications up to 2022. We studied them through three categories and presented the quantitative and qualitative results. These findings led us to propose our perception of the supply chain in the context of the physical Internet and in particular the issues of considering a supply network instead of a supply chain. Finally, we raised questions and proposed research opportunities before concluding.

Keywords: *Physical Internet, Supply Chain, Logistics, Mathematical Programming, Literature Review*

1. INTRODUCTION

If the development of digital technology has facilitated the growth of e-commerce, the recent pandemic has disrupted the purchasing process and strongly impacted supply chains which must adapt in order to maintain their performance level. Faced with a situation of unsustainability of supply chains [1] new concepts are emerging with a new vision inspired by exchanges in computer networks. One of them is the Physical Internet, a disruptive concept that promises to change "the way physical objects are handled, moved, stored, produced, supplied and used, aiming at the efficiency and sustainability of global logistics" [2].

The Physical Internet is a concept inspired by the Digital Internet. In the Physical Internet, products are encapsulated in smart containers and routed through multiple nodes between source and destination. Thus, we can take advantage of advances in information technology to develop the Physical Internet and to accelerate its implementation. This further expands the scope of application of Digital Internet technologies and business models in the field of logistics and supply chain.

In recent years, several publications have contributed to the development of the Physical Internet on technical, technological, commercial aspects - through economic models - and in terms of governance [3]. This work deals specifically with mathematical programming and optimization in logistics and supply chains that use the Physical Internet. To the best of our knowledge, this is the first work that brings together all publications based on mathematical programming in the context of the Physical Internet. It is a contribution to help researchers review and compare the models used to identify potential directions of research. It also opens the possibility to extrapolate the adaptations of the models, built for the Physical Internet, in the classic supply chain management.

Within this scope, this paper aims to answer the following research questions: (1) does the current literature on the Physical Internet cover all the nodes and links in a supply chain? (2) how does the current literature formulate and model the problems of supply chains in the context of the Physical Internet? (3) The Physical Internet plans to address sustainability issues. What dimensions of sustainability are modeled? To this end, we analyzed the literature with a focus on supply chain nodes and links. Then, we classified the analyzed publications according to the problems presented. Then, we extracted the approaches and resolution tools adopted. Finally, we identified the sustainability dimensions addressed.

This work is structured in five sections. The first section is devoted to a brief presentation of the Physical Internet. In the following two sections, we will detail the methodology adopted and the results. The fourth section will be dedicated to highlighting opportunities for contribution. Finally, we will conclude our research in the fifth section.

2. BACKGROUND: THE PHYSICAL INTERNET

The Economist's June 2006 special edition of a collection of articles and logistics studies was titled "The Physical Internet". In this publication, the authors did not explain the concept. They briefly alluded to the idea by describing the similarities between computer networks, routers and data packets on the one hand and logistics networks, warehouses and physical boxes on the other [4].

This metaphor presents a new perspective that could consolidate the various singular initiatives to improve the performance of supply chains [3]. Hence the interest of researchers [5]. The use of the term "Physical Internet" with its current meaning goes back to the publication by B. Montreuil of the first "Manifesto for a Physical Internet" [6]. Followed by a vision of the concept that responds to the inefficiency and the economic, environmental and social unsustainability of the current logistics [1]. Later, the Physical Internet was defined as "an open global logistics system founded on physical, digital and operational interconnectivity through encapsulation, interfaces, and protocols. It is a perpetually evolving system driven by technological, infrastructural and business innovation " [7].

The literature presents the Physical Internet as a solution that aims to the universal interconnection of logistics networks between suppliers and consumers [8]. However, the cases analyzed in the literature still separate between the different flows (raw material, reverse logistics, distribution, last mile, ...). For example, the flows between supplier and retailer [9]–[11] are presented independently from the flows between retailer and consumer [12]–[14]. And even when reverse logistics is discussed, it is dissociated from direct logistics [15]. We believe that the objectives and interests of the Physical Internet would only be fully achieved through a level of integration and massification of flows that is never thought of before. An integration including all flows and all actors. For example, massifying the flows of reverse logistics with the flows suppling factories with raw materials while sharing the same infrastructure as direct logistics through the Physical Internet network.

To represent the flow dynamics of a supply chain, the Forrester model [16] has been shown to be an important reference [17]. Some models present other complementary flows such as reverse logistics [18]. To illustrate our perception of the Physical Internet, we propose to transcribe these models as shown in Figure 1. This illustration shows an abstraction of the supply chain through the Physical Internet where each link between actors systematically goes through a sub-network of the Physical Internet as presented in Figure 2

In this work, we will use this model (Figure 1) to classify publications and determine which segments are covered by the literature and therefore which segments require more attention.

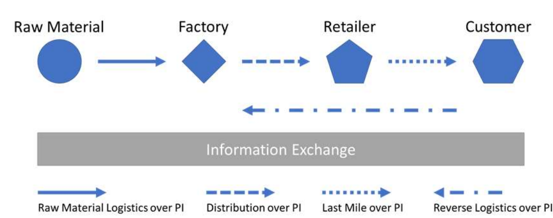

Figure 1. The supply chain through the Physical Internet

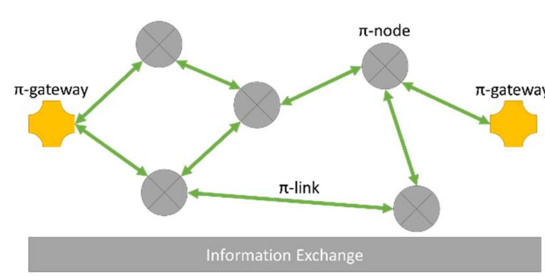

Figure 2. Abstraction of a subnet of the Physical Internet

3. METHODOLOGY

The methodology considered for this work is inspired by the approach of Seuring and Gold [19] which is based, among others, on the work of Mayring [20], [21]. This approach frames and structures the research to obtain objective results while facilitating the distribution of the work in several teams or through several iterations. Thus, the "Qualitative Content Analysis" method was applied through four steps ("Collection", "Analysis", "Categorization", "Evaluation") as illustrated in Figure3

Figure3. The four steps of the Qualitative Content Analysis method

3.1. Data collection

The physical Internet remains a new topic as illustrated by the statistics that will follow. To have the most complete vision of the subject, we have used several databases: Scopus, ScienceDirect and Web of Science. We have built a search base for publications up to January 2022. The exact term "Physical Internet" was searched in the title, keywords and abstract as shown in Table 1 Separating the terms "Internet" and "Physical" returns results that are related to the Digital Internet and the physical location of the Digital Internet infrastructure. These latter elements do not correspond to the topic of this paper.

Table 1. Databases and searched expression.

Database	Searched expression	Fields	Papers
Scopus	« Physical Internet »	Title, keywords, and summary	273
Web of Science			132
ScienceDirect			73

3.2. Data analysis

In addition to the exact criteria we used, the search results had to be analyzed to ensure their relevance and appropriateness to the Physical Internet and the scope addressed by this paper, namely modeling through mathematical programming. Thus, the 478 publications found were reprocessed in several iterations.

We analyzed each publication gradually until we got the desired metadata. We examined the contributions in this order: (1) the title and keywords, (2) the abstract, (3) the conclusion, (4) the introduction, and (5) the entire article. This iterative process, illustrated in Figure 4 allowed us to gradually eliminate:

- Papers where the term "Physical Internet" refers to the physical infrastructure of the Digital Internet.
- Papers referring to the "physical Internet" as a concept for illustrative purposes.
- Papers referencing the "physical Internet" as the framework towards which the elements studied by the researchers will converge.
- Review works.
- Papers dealing with "the physical Internet" but not addressing mathematical modelling.
- Papers formalizing models for the "physical Internet" without relying on mathematical programming.
- Papers written in a language other than English.

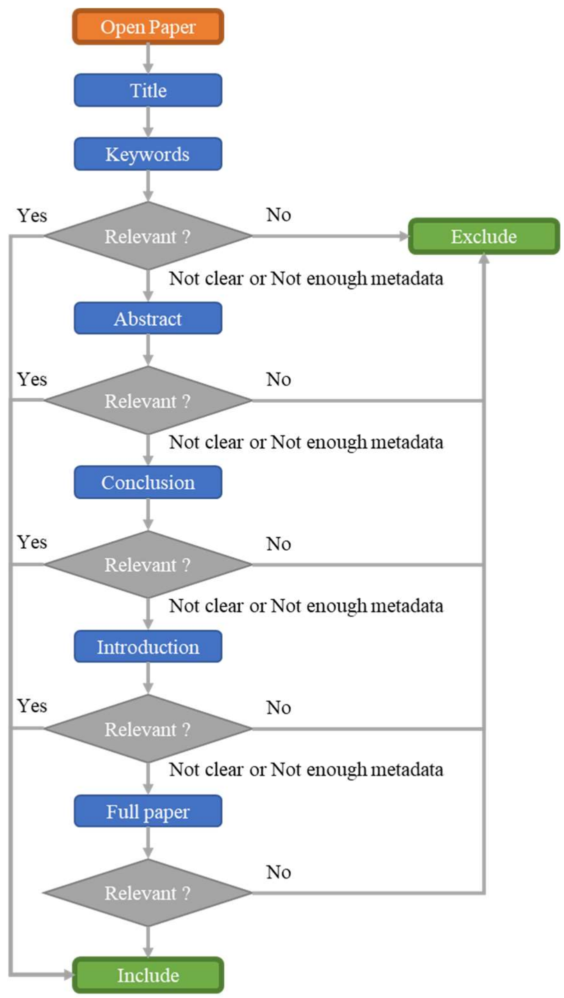

Figure 4. Document analysis process

3.3. Data categorization

To simplify the comparison of publications and the identification of contribution tracks, we propose the following three categorizations:

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

1. Supply chain coverage
2. Formulated and modeled problems
3. Addressed sustainability dimensions

3.3.1. Categorization by supply chain coverage

In an effort to contribute to the acceleration of the deployment of the Physical Internet, we propose a classification to indicate the elements of the supply chain covered by the contributions. This will allow to highlight the elements that are of most interest to the research community.

We will use the schema presented in Figure 1 for this categorization to provide both a global and detailed view. Indeed, we will be able to assess whether the entire supply chain is covered by the contributions as well as the distribution of this coverage across the nodes and links of the chain.

For this categorization, we will indicate for each publication, if it studies the nodes of the supply chain, the links between nodes, or functions performed at a node level.

3.3.2. Categorization by formulated and modeled problems

As a matter of fact, the physical Internet is a new, efficient and promising concept [12]. It is supposed to provide solutions or at least contribute to the simplification of classical supply chain problems (location problem, vehicle routing problem, etc.). We wish to classify the publications according to the classical problem addressed. This classification will allow researchers interested in the Physical Internet to complete the contributions and enrich them with direct access to publications addressing these problems. The classification should also allow researchers interested in supply chain, logistics, or transportation problems to potentially identify in the Physical Internet a different vision that will allow them to address classical problems from a new angle.

In the analyzed publications, the reference (classical) problem is not always mentioned. Therefore, we tried to approach this categorization by extracting the descriptions of the problems proposed by the authors and by analyzing and categorizing the objective functions according to the nature of the optimized elements. This work allowed us to identify eight categories to which the optimized elements in the objective functions refer: handling, stock, order, transport, production, building, penalty and showcasing.

Also, in order to identify potential new approaches to solving the problems of the Physical Internet, or the supply chain in general, we have identified the methods and technical tools used for solving them.

3.3.3. Categorization by the addressed sustainability dimension

The Physical Internet is designed to respond to the symptoms of unsustainability by addressing the economic, environmental and social dimensions [1]. This is another categorization that we propose for the selected papers. This will allow researchers interested in a specific dimension to quickly access contributions dealing with that dimension in order to identify gaps and opportunities for contribution.

For this categorization, the publications will be classified according to the dimension addressed: economic, environmental or social.

3.4. Evaluation

The categories were established and shared among the research group with the process to follow Figure 4. Results were compared then differences were discussed to remove doubt about the assignment of a contribution to a category. This approach is recommended by Seuring and Gold [19] to ensure reproducibility, transparency and objectivity. Once the classification was completed it was reviewed to ensure that it was consistent with the purpose of the contribution.

4. FINDINGS

4.1. Quantitative findings

The dataset before duplicate removal contains 111 publications. Scopus has the largest share, followed by WebOfScience and finally ScienceDirect with 57, 35 and 19 publications respectively. After removing the duplicates, the dataset contains only 60 publications. For the rest of this work, this is the dataset that will be considered.

Figure 5, shows three main phases: before 2015, between 2015 and 2019, and after 2019. Indeed, before 2015, we have a relatively constant number of publications. After 2015, we have seen a significant increase in contributions with a clear growth trend. The first international conference on the physical Internet organized in 2014 could explain the variation between these two periods. This event therefore contributed to the spread of the concept. From 2019, the number of publications doubled (12) compared to the second phase (6 on average). A trend maintained in 2022 with 3 publications from the first month.

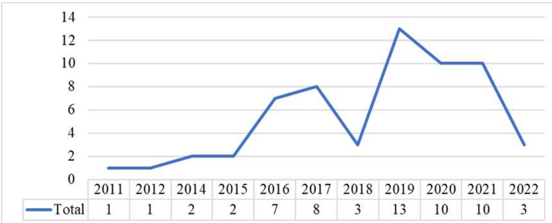

Figure 5. Publications over time

We also noticed a stagnation or a slight decrease in publications in 2018. This could be due to the time it takes to prepare publications. In fact, we observed that the average publications in 2018 and 2019 exactly match the trend in 2016 and 2017.

To better assess the interest of authors and especially new authors, we analyzed publications by author (all authors in the publication are considered regardless of their order in the author list) in three different ways: (1) the total number of publications per author per year, (2) at least one publication for each author per year, and (3) the first publication of an author (new author). We restricted ourselves to full years in order to interpret the trends. Thus, Figure 6 shows a constant evolution for the three plots indicating a growing interest in the Physical Internet. Especially since curve (3) indicates that the number of new researchers is growing.

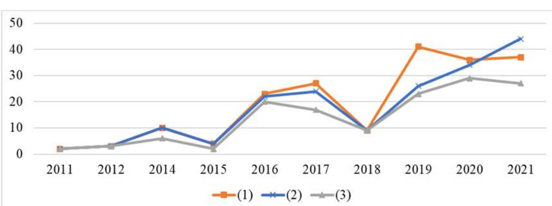

Figure 6. Analysis of publications by author

Table 3 shows that the first publications were mainly in the form of "Conference Paper" with a change in trend in 2016 in favor of the "Article" form which have a share of 54% of all publications.

As for the authors, 151 unique contributors were found. The first 5 authors contributed to 31 publications, which represents 52% of all publications. These authors are Eric Ballot, Shenle Pan and Abdelghani Bekrar with 7 contributions each, then Benoit Montreuil and Damien Trentesaux with 5 publications each. This indicates a concentration of publications in a few research groups.

The selected publications were published in 27 journals. The journal with the highest number of publications is "International Journal of Production Research" with 18 publications, followed by "IFAC-PapersOnLine" with 7 publications, then "Computers and Industrial Engineering", "International Journal of Production Economics" and "Lecture Notes in Computer Science" with 3 publications each. Those 5 journals published 57% of the contributions.

4.2. Supply chain coverage

Table 4 presents the result of our analysis of the publications in relation to the nodes and links of the supply chain as shown in Figure 1. Since the distribution logistics are detailed in the publications with the "Factory Warehouse" and "Distributor" nodes, we have included those nodes by mapping them to the π-nodes of the Physical Internet. The full mapping is presented in Table 2.

Table 2. The complete mapping of supply chain nodes and links in the current vision and from the perspective of the physical Internet.

Current Vision	**Physical Internet Vision**	**Abbreviation**
RAW	RAW	R
<=>	<π>	R-F
Factory	Factory	F
<=>	<π>	F-W
Factory WH	π - node	W
<=>	<π>	W-D
Distributor	π - node	D
<=>	<π>	D-L
Retailer	Retailer	L
<=>	<π>	L-C
Customer	Customer	C

According to Table 4 the flow of raw materials to factories has not been treated explicitly. That is also the case for the end-consumer node.

The "Factory Warehouse" and "Distributor" nodes are the most covered elements with 32 publications each. They are followed by the "Retailer" node with 14 publications. Then, the "Factory" node with 10 publications.

When it comes to links, "Distributor > Retailer" is the most covered with 32 publications. It is followed by the link "Factory Warehouse > Distributor" with 29 publications. Then the link "Factory > Factory Warehouse" with 26 publications. Finally, the link "Retailer > Customer" with 10 publications.

The assignment of the publications to the categories "Retailer" and "Retailer > Customer" was

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

not obvious because these two elements are involved in several configurations of the supply chain. For some publications (for example [9] or [10]), the "Retailer" is the end of the scope of the Physical Internet. For others (for example [22]), it is the beginning of a new scope towards the end customer.

To maintain a coherent vision and preserve the connection with the different configurations of the Physical Internet, we have considered that the "Retailer" node provides the following functions:

- It is the final point where the consumer buys the products (and therefore consumes them).
- It is an interface with the consumer in the way that it allows the consumer to interact indirectly with the Physical Internet.
- It is a shipper for the products to be delivered to the end customer. As such, it is the entry point for a new configuration of the Physical Internet.

4.3. Formulated and modeled problems

Table 5, summarizes the work on the formulated problems by recalling description of the problem and the analysis of the elements of its objective function.

The modeled problems are not formulated in a way that helps their classification. We have found it more useful to summarize their formulation as presented in each paper. Subsequently, we will propose some interpretations in the next section.

Regarding the analysis of the objective function elements (H = Handling, I = Inventory, L = Location, O = Ordering, N = Penalty, P = Production, T = Transportation, S = Showcase Value), we found the following:

- 53 (or 88%) publications cover the subject of transportation. The main costs considered are: the overall costs without precision ([10], [14], [23]–[42]), costs based on distance ([11], [43]–[48]), costs related to loaded volume ([44], [49]–[54]), fixed costs ([13], [36], [51], [55]–[57]), costs based on time ([12], [26], [58]–[61]), variable costs ([9], [13], [51], [55], [57]), etc. Contributions also address transportation sustainability through energy costs ([10], [56], [62], [63]), greenhouse gas emissions ([10], [11], [24]–[26], [60]) and work accidents ([10]).
- 11 publications introduce a penalty in the objective function. The lateness penalty remains the most considered ([13], [31], [36], [39], [51], [64]). Followed by the penalty for unmet requests ([12], [34], [51]). Then, the penalty of requests unmet immediately ([28], [29]) and the penalty of lost sales ([9], [38]).
- 11 publications deal with production. 5 contributions consider set-up and variable costs ([9], [10], [24], [25], [38]), 4 use fixed costs ([9]–[11], [58]) and 4 others use labor costs ([24], [25], [58], [65]). 3 publications deal with time ([11], [65], [66]), 3 cover greenhouse gas emissions ([10], [24], [25]) and 3 consider costs of production tasks ([58], [65], [67]). Energy consumption is addressed by 2 works ([24], [25]) and work accidents are covered by [10]. Finally, [38] considers backup and restoration costs of production.
- 10 publications consider inventory. 6 works do not specify the nature of the costs ([9], [10], [31], [32], [38], [51]) and 5 works study the cost related to stock holding ([11], [28]–[30], [38]).
- 9 works deal with the handling of products or their containers. [27], [29], [35], [38], [56], [57] do not specify the nature of the costs. [64], [68] use the distance travelled. [10] addresses loading, unloading, greenhouse gas emissions and work accidents. Finally, [23] discusses energy.
- 8 publications take into account facilities : unspecified ([27], [33], [35]), construction ([32], [37], [40], [42]), fixed costs ([40], [41]), variable costs ([40]) and last, the number of buildings [41].
- 4 publications refer to ordering in terms of fixed costs ([28], [29], [34]) or fillability ([22]).
- [69] deals with the selection of products to showcase taking advantage of an infrastructure based on the Physical Internet.

We also conducted a review of approaches and resolution tools as presented in Table 6.

We identified 38 approaches used for solving the formulated problems. These approaches include heuristics and meta-heuristics, algorithms, and simulation approaches.

From Table 6 we can notice that "Simulation" and "Simulated Annealing" are the most used approaches, followed by "Neighborhood Search", "Source selection strategy" and "Branch-and-Bound", then, "Tabu Search" and "Multi Agent". Finally, the other approaches were used only once each.

7 publications ([13], [26], [52], [62], [65], [67], [70]) provide specific heuristics and 3 works ([31], [36], [44]) propose specific algorithms.

In terms of tools, CPLEX remains the most widely used tool. Martlab comes in second place and Mathematica in third. It is worth mentioning that 16

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

publications did not explicitly specify the solving tools used.

4.4. Addressed sustainability dimensions

All the analyzed papers propose cost minimization or profit maximization. Thus, all 60 publications address the economic dimension. The environmental dimension is addressed by 8 publications [10], [11], [13], [23]–[26]. While the social dimension is covered by only 2 publications [10], [13].

We also found two publications that address all 3 dimensions at once. For [10], the dimensions are included in the formulation of the objective functions. Meanwhile, [13] does not integrate them explicitly into the objective function but indicates the adaptation to be made to its formulation in order to integrate these dimensions.

5. DISCUSSION

In this section we will discuss the results of the review by following the categorizations presented at the methodology section.

5.1. Supply chain coverage

As shown in the previous section, no publication deals with the end-to-end supply chain (from raw material to final consumer through last mile delivery). This leads us to believe that the concept is still treated by reference to classical supply chain configurations. In fact, the literature studies the actors in the context of a chain. While the Physical Internet allows us to revise the model of a supply chain using a web. Figure 7presents our perception of the classical supply chain ([16], [18]) as a web. We believe that for a better perception of the Physical Internet, we must consider and reason in terms of a supply network and not a supply chain. In this context, the focus is on the optimal management of flows, regardless of origin or destination, through the network. This allows, for example, the massification of raw material and reverse logistics flows when the production area of the raw material and the consumption area of the finished products are close. Also, let us recall that some means of transportation even allow the mutualization of passenger flows with the goods flow ([12]). We consider that this perception of the web supply chain presents a potential field for research and modeling.

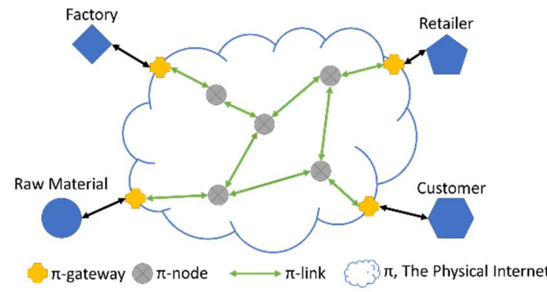

Figure 7. Our perception of the supply chain with the Physical Internet

Thus, while the literature does not cover the raw material part, we believe that this is a special case that will be natively supported by the Physical Internet with the vision presented in Figure 7.

The "Factory Warehouse", "Distributor", "Retailer" and "Factory" nodes are relatively well covered. We believe that this is primarily due to the nature of the products studied, i.e., consumer products in modern distribution channels. This also explains the coverage of the links "Distributor > Retailer", "Factory Warehouse > Distributor" and "Factory > Factory Warehouse". Other industries such as aeronautics or textiles are not studied in the literature on the Physical Internet and their analysis could further complete the vision of the Physical Internet.

We have noted that the "Retailer > Customer" link is relatively less covered as the demand for e-commerce solutions increases. We believe that the key lies in π-containers and new means of transportation (autonomous electric vehicle, drones, ...). Thus, the Physical Internet can change the perception of the last mile. By drawing a parallel with the Digital Internet, we can imagine that consumers would be "connected" to the Physical Internet network as they are today to the Internet network. In this context, we believe that it is possible to consider the "Dabbawala" concept [71] as a real and efficient application of the Physical Internet for the last mile.

5.2. Formulated problems

Within the analyzed literature, the formulated problems address a part of the supply chain. [9]–[11], [30], [38] are the publications that cover the largest number of nodes and links. These publications study the problems of Production, Inventory, Location and Distribution. They do not deal with the raw material part and the delivery to the final consumer. This leads to the question about the global optimum and the sum of the local optima. In this context, will we obtain a global optimum of the supply chain through the Physical Internet by

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

combining the local optimums of the segments of the chain? Or could we obtain a global optimum for the supply chain through the Physical Internet regardless of the existence or absence of local optimums?

In this same context, we ask ourselves a question regarding the optimization of transport and especially routing. Classically, routing optimizations are combined with other optimizations such as location (Location Routing Problem), inventory (Inventory Routing Problem), production-distribution (Production Distribution Routing Problem), or production-stock-distribution (Production Inventory Distribution Problem). With the Physical Internet, would it be relevant to address routing in combination with the other topics or independently of them? The perception presented in Figure 7 suggests that routing should be optimized independently of the other topics, especially since the massification effect enabled by the Physical Internet may be superior to the other optimizations. Further analysis is required, then, to confirm or deny this assumption.

Likewise, the analysis of the proposed models, in terms of prerequisites for the use of the models, reveals the need to know the demand at the nodes of the chain for the optimizations. This assumes that this demand is known in advance on the whole network in order to calculate the optimal or near-optimal configuration. We believe that this condition is not feasible in practice. Not only can demand be uncertain, but also other key parameters of supply chain decisions. In fact, the dynamics of relationships among different actors in supply chains include uncertainty, especially in planning decisions [72]. Uncertainty remains a major factor influencing the effectiveness of supply chain configuration and coordination [73].

To draw a parallel with the Digital Internet, from which the Physical Internet is inspired, let's imagine that we need to know all the users' flows in order to route the data packets through the network! And even if this data exists, imagine the computational power needed to find the optimums without compromising the transmission delays (and the delivery constraints of the physical world). It is thus clear that the proposed optimizations can work on a small scale but not to manage a global network based on the Physical Internet. Hence the need to create models that do not necessarily have knowledge of the global network but only of the sub-network they manage. Models that are highly responsive and adaptive, able to reconfigure the path between a source and a destination based on requirements and risks. This agility is provided by the Physical Internet through π-containers and the intelligence they carry. Future models could also favor local and real-time optimizations based on the information collected by the π-containers. For this purpose, researchers could explore fuzzy models to address this challenge.

Furthermore, not all the operations of handling π-containers are covered with respect to the operations described in [74] i.e., receiving, testing, moving, routing, sorting, handling, placing, storing, picking, checking, labeling, paneling, assembling, disassembling, folding, clipping, unclipping, composing, decomposing and shipping. Thus, the operations not yet covered are: testing, picking, checking, labeling, paneling, assembling, disassembling, folding, clipping and unclipping. Some of these operations are likely to be considered as production or planning problems and require further research. For this purpose, it should be noted that multimodal operations between road and rail are the only ones studied. Air and river, and even other modes, present opportunities for investigation.

5.3. Addressed sustainability dimensions

Environmental and social sustainability are still poorly covered in the literature reviewed. Environmental sustainability is analyzed mainly in terms of greenhouse gas emissions. Social sustainability is treated in terms of working hours for drivers and in terms of accidents.

With reference to the sustainability models presented by Ivete Delai and Sergio Takahashi [75] other components of sustainability could be treated. For example, air is only studied through greenhouse gas emissions, whereas the impact on human health can also be studied. Land, energy, water, biodiversity and the contribution of products and services to environmental sustainability remain to be studied.

Similarly, [75] presents 5 themes for the social dimension: decent work practices, customer relationship management, corporate citizenship, suppliers and partners, public sector. The literature only deals with incidents on the physical health of operators, which are part of decent work practices. The other themes remain to be explored.

6. CONCLUSION

The Physical Internet is a new concept that provides a new vision of supply chains. Based on the Digital Internet, it consists of encapsulating products in intelligent containers and routing them through a set of nodes between the source and the destination.

In this paper, we presented a review of the Physical Internet literature that relies on mathematical programming to answer three questions: (1) what is the coverage of nodes and links of a supply chain by the current Physical Internet literature? (2) What mathematical programming models are used for modeling and optimizing supply chains in the context of the Physical Internet? (3) How are sustainability aspects addressed by the proposed models?

For this review, we used the "Qualitative Content Analysis" method through which we identified a categorization of publications for each of the questions asked. Thus, we evaluated 60 publications selected from three databases (Scopus, WebOfScience and ScienceDirect) until 2022.

The quantitative analysis was performed according to source, year, type of publication, author and journal where the work was published. This analysis reveals that Scopus contains the largest number of publications. The number of authors is growing, which indicates the interest of the subject in the scientific community. The novelty of the subject and its potential are confirmed by the concentration of publications in small research groups led by a few researchers.

For the coverage of the supply chain, the "Factory Warehouse" and "Distributor" nodes are the most studied elements. When it comes to linkages, the "Distributor > Retailer" and "Factory Warehouse > Distributor" links are the most studied. The raw material and end consumer nodes are not directly covered in the literature.

In terms of modeling, transportation remains the most studied topic. It is followed by inventory and product handling. In terms of resolution, the "Simulation", "Simulated Annealing" and "Neighborhood Search" approaches are the most used. Specific heuristics and algorithms have been used sometimes for the resolution of some models. In terms of tools, CPLEX is by far the most used. It is followed by Martlab and Mathematica.

The economic sustainability is treated (explicitly or implicitly) by all the contributions. On the other hand, the social and environmental aspects are not very well addressed.

Moreover, after the analysis of these publications we came to some conclusions. First, the web-based perception of the supply chain in the context of the Physical Internet presents important research and modeling opportunities. The main goal is to create an efficient system that supports the flow from the raw materials to the end customer with a global dimension. Second, the concept of the Physical Internet can evolve more rapidly with the study of other sectors and industries such as aeronautics and textiles, to name a few. Then, we have raised the issue of local and global optima with the supply chain web vision. This question arises for routing as well as for the information to be provided to find the optimal or near-optimal configurations. We need highly responsive and adaptive models that can reconfigure the path between a source and a destination based on requirements and risks. Finally, the sustainability of the physical Internet can benefit from an extension of the dimensions currently analyzed by integrating the impact on water or land for the environmental aspect or the creation of jobs and their attractiveness for the social aspect.

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Table 3. Publication by type over time

Type	2011	2012	2014	2015	2016	2017	2018	2019	2020	2021	2022	Total
Article			2	1	4	6	2	12	5	5	1	38
Conference Paper	1	1		1	3	2	1	1	3	4		17
Research article									1		2	3
Book Chapter									1	1		2
Total	**1**	**1**	**2**	**2**	**7**	**8**	**3**	**13**	**10**	**10**	**3**	**60**

Table 4. Analysis of publications according to our perception of the supply chain through the Physical Internet

Ref.	R	R-F	F	F-W	W	W-D	D	D-L	L	L-C	C
[39]				X	X	X	X	X			
[43]					X	X	X	X	X		
[76]					X		X				
[40]				X	X	X	X	X	X		
[64]					X		X				
[69]									X		
[77]				X		X		X			
[23]					X		X				
[9]			X	X	X	X	X	X	X		
[10]			X	X	X	X	X	X	X		
[68]					X		X				
[41]									X		
[78]				X		X		X			
[11]			X	X	X	X	X	X	X		
[49]					X		X				
[22]									X		
[12]										X	
[42]					X		X		X		
[27]				X	X	X	X	X			
[28]					X	X	X	X	X		
[50]					X		X				
[58]				X	X	X	X	X			
[29]					X	X	X	X	X		
[13]										X	
[14]								X		X	
[51]				X		X		X			
[52]					X		X				
[44]					X		X				
[30]			X	X	X	X	X	X	X		
[31]				X	X	X	X	X			

[65]			X								
[66]			X								
[32]				X	X	X	X	X			
[79]										X	
[33]				X	X	X	X	X			
[34]				X	X	X	X	X	X		
[45]					X		X				
[53]					X		X				
[70]					X		X				
[54]					X		X				
[35]								X		X	
[62]				X		X		X			
[36]										X	
[24]			X	X	X	X	X	X			
[25]			X	X	X	X	X	X			
[37]										X	
[55]				X		X		X			
[63]				X		X		X			
[38]			X	X	X	X	X	X	X		
[67]			X								
[59]				X		X		X			
[80]				X		X		X			
[26]				X		X		X			
[46]										X	
[60]					X		X				
[47]								X			
[56]										X	
[48]										X	
[61]				X		X		X			
[57]				X		X		X			
Count	**0**	**0**	**10**	**26**	**32**	**29**	**32**	**32**	**16**	**10**	**0**

Table 5. Elements covered in objective functions

Ref.	Problem Description	H	I	L	O	N	P	T	S
[39]	Multi-commodity network flow model, Less-Than-truckLoad collaboration					X		X	
[43]	Assigning retailers to clusters							X	
[76]	Carrier request selection							X	
[40]	Capacitated, deterministic hub network design model			X				X	
[64]	Scheduling both inbound and outbound trucks as well as grouping of PI-containers in the train's wagons and outbound trucks	X				X		X	
[69]	Showcasing value								X
[77]	Carrier allocation to transportation request (Winner Determination							X	

	Program)								
[23]	Find the grouping of the PI-containers and the assignment and scheduling of the trucks at the docks.	X						X	
[9]	Production, Inventory, Distribution		X			X	X	X	
[10]	Production, Inventory, Distribution	X	X				X	X	
[68]	Road-Rail scheduling and grouping problem	X						X	
[41]	Vertex cover, Facility Location Problem, Location Routing Problem, Vehicle Routing Problem			X				X	
[78]	Carrier allocation to transportation request (Winner Determination Program)							X	
[11]	Flexible Job Shop Scheduling and Rescheduling Problem With Inventory and Transportation optimization		X				X	X	
[49]	Multiple heterogeneous Knapsack Problem							X	
[22]	Dynamic stocking problem				X				
[12]	Matching riders with drivers					X		X	
[42]	Capacitated, deterministic hub network design model			X				X	
[27]	Liner Shipping Network Design Problem, Multi-Commodity Flow Problem	X		X				X	
[28]	Single product inventory problem with uncertain demands and stochastic supply disruptions		X		X	X		X	
[50]	Constraint Satisfaction Problem, Container loading problem							X	
[58]	Bin Packing Problem, Vehicle Routing Problem, Job Scheduling						X	X	
[29]	Vendor-managed Inventory Problem	X	X		X	X		X	
[13]	Vehicle Routing Problem with Pickup and Delivery Problem					X		X	
[14]	Optimizing e-commerce delivery scheduling							X	
[51]	Groupage transportation, including consolidation and deconsolidation centers in the network nodes where goods are loaded/unloaded into/out from containers		X			X		X	
[52]	Bin Packing Problem							X	
[44]	Smart boxes Loading Problem							X	
[30]	Multi-plant, Production planning and Distribution Problem		X				X	X	
[31]	Shipment Consolidation Problem		X			X		X	
[65]	Job-shop Scheduling Problem						X		
[66]	Hybrid Flow shop Scheduling Problem					X	X		
[32]	Distribution Network Design Problem		X	X				X	
[79]	Vehicle Routing Problems, Pick-up and Delivery Problem, Stacker Crane Problem							X	
[33]	Distribution Network Design Problem			X				X	
[34]	Replenishment Policy optimization				X	X		X	
[45]	Cross-Docking Terminal Problem							X	
[53]	Container Loading Problem							X	
[70]	Bin Packing Problem							X	
[54]	Container Loading Problem							X	
[35]	Network Design Problem, Vehicle Routing Problem	X		X				X	
[62]	Platooning in a Physical Internet based logistics network							X	
[36]	Dynamic Pickup and Delivery Problem with Time Windows					X		X	

Journal of Theoretical and Applied Information Technology
28th February 2022. Vol.100. No 4
2022 Little Lion Scientific

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

[24]	Hyperconnected mobile modular production with environmental consideration						X	X	
[25]	Hyperconnected mobile modular production with environmental consideration						X	X	
[37]	Multi-echelon networks for urban distribution			X				X	
[55]	Multi-Commodity Network Design							X	
[63]	Platooning in a Physical Internet based logistics network							X	
[38]	Production Inventory Distribution Problem	X	X			X	X	X	
[67]	Graduation Intelligent Manufacturing System						X		
[59]	Vehicle Routing Problem with Pickup and Delivery							X	
[80]	Minimizing flow imbalances of pi-containers between the origin and destination hubs							X	
[26]	Single-source Shortest Path Problem							X	
[46]	Vehicle Routing Problem, Bin Packing Problem, Vehicle Dispatching Problem							X	
[60]	Truck scheduling and PI-containers routing in Road-Road PI-hub							X	
[47]	Vehicle Routing Problem, Dynamic Multiple Depots Vehicle Routing							X	
[56]	Vehicle Routing Problem with simultaneous Pick-up and Delivery	X						X	
[48]	Order fulfillment and replenishment							X	
[61]	Vehicle Routing Problem with Pickup and Delivery							X	
[57]	Selective vehicle routing problem	X						X	
Count		**9**	**10**	**8**	**4**	**13**	**11**	**53**	**1**

Table 6. Resolution approaches and tools

Ref.	**Solving Approach**	**Solving Tools**
[39]	Local search heuristic Simulated Annealing	-
[43]	-	CPLEX
[76]	-	Mathematica
[40]	-	General Algebraic Modelling System
[64]	Modified Threshold Accepting meta-heuristic	CPLEX C++
[69]	-	-
[77]	Freight Transportation Game Simulation	Matlab
[23]	Lexicographic Goal Programming Simulated Annealing Tabu Search Variable Neighborhood Search	CPLEX
[9]	-	CPLEX
[10]	Pareto	CPLEX
[68]	Greedy Randomized Adaptive Search Procedure Multi Agent Simulated Annealing Tabu Search Variable Neighborhood Search	CPLEX

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

[41]	2opt algorithm ADD algorithm Branch-and-Bound Sweep algorithm	Fico Xpress
[78]	Multi Agent Simulation	Matlab
[11]	Particle Swarm Optimization	CPLEX
[49]	Heuristic Weight first best fit	CPLEX Python
[22]	Heuristic Highest Inventory Imbalance Heuristic Longest Stocking Gap	MS EXCEL + OpenSolver VBA
[12]	Branch-and-Bound MAThematical programming HEURISTIC	CPLEX
[42]	-	CPLEX
[27]	Lagrange heuristic Variable Neighborhood Search	CPLEX
[28]	Simulated Annealing Source selection strategy Simulation	Mathematica
[50]	-	Matlab
[58]	Monte-Carlo Simulation Simulation	Gurobi
[29]	Simulated Annealing Source selection strategy Simulation	Mathematica
[13]	Specific Heuristic	CPLEX
[14]	Ant algorithm	Matlab
[51]	-	CPLEX
[52]	Specific Heuristic	- C Language
[44]	Specific Algorithm	-
[30]	Branch-and-Bound	CPLEX
[31]	Specific Algorithm	Gurobi
[65]	Specific Heuristic	-
[66]	-	Matlab
[32]	-	-
[79]	Dynamic matching strategy	CPLEX
[33]	-	CPLEX
[34]	Simulated Annealing Source selection strategy	Mathematica
[45]	Asynchronous sorting Simulation	Simulation: FlexSim, Optimizer: OptQuest
[53]	Decomposition-based methodology First Fit Decreasing	-
[70]	Specific Heuristic	AnyLogic
[54]	-	-
[35]	-	CPLEX
[62]	Heuristic-based algorithm Reinforcement Learning-based Algorithm	-

[36]	Specific Algorithm	Python
[24]	-	CPLEX
[25]	-	-
[37]	-	-
[55]	General Cuts Symmetry Breaking Cut Arc Residual Capacity Cut Cutset Cut Strong Cut	CPLEX
[63]	-	-
[38]		Python; Gurobi
[67]	Specific Heuristic	-
[59]	Simulated Annealing (Threaded with Memory) Neighbourhood search	CPLEX; Java
[80]	Simulation	-
[26]	Specific heuristics (reachability and optimality)	-
[46]	Insertion heuristics Bottom-Left-First heuristic	CPLEX
[60]	-	CPLEX
[47]	Iterated Random Heuristic Nearest Neighbour Search	CPLEX
[56]	Genetic algorithm Neighbourhood Search	Matlab
[48]	Simulation	-
[61]	Discrete event simulation Biased randomized multi-start Biased randomized iterated local search	CPLEX; Java
[57]	Adaptive Large Neighborhood Search	CPLEX