Acta logistica - International Scientific Journal about Logistics
Volume: 8 2021 Issue: 3 Pages: 217-227 ISSN 1339-5629

doi:10.22306/al.v8i3.224 *Received: 30 Mar. 2021; Revised: 15 Apr. 2021; Accepted: 15 June 2021*

APPLICATION OF PHYSICAL INTERNET IN INTRALOGISTICS – A SIMULATION STUDY

Eszter Puskás
Budapest University of Technology and Economics, Faculty of Transportation Engineering and Vehicle Engineering, Department of Material Handling and Logistic Systems, Műegyetem rakpart 3. Budapest H-1111, Hungary, EU, eszter.puskas@logisztika.bme.hu
Gábor Bohács
Budapest University of Technology and Economics, Faculty of Transportation Engineering and Vehicle Engineering, Department of Material Handling and Logistic Systems, Műegyetem rakpart 3. Budapest H-1111, Hungary, EU, gabor.bohacs@logisztika.bme.hu (corresponding author)
Levente Zakariás
Budapest University of Technology and Economics, Faculty of Transportation Engineering and Vehicle Engineering, Department of Material Handling and Logistic Systems, Műegyetem rakpart 3. Budapest H-1111, Hungary, EU, zakarias.levente@edu.bme.hu

Keywords: logistics, Physical Internet, intralogistics, simulation
Abstract: One of the biggest challenges today is to make traditional systems more sustainable. Physical Internet (PI, π) based logistics systems provide one of the most defining solutions. In our opinion, it is worthwhile to deal with the intralogistics conversion of the Physical Internet because traditional systems can no longer operate with sufficient efficiency to meet growing customer expectations and demands. This research focuses on restructuring a factory from its traditional operating to a PI-based system using our previously defined intralogistics components. The article surveys the possibility of creating PI-hub and virtual PI-hub in a factory process. The warehouses were converted to PI-hubs, and virtual PI-hubs were placed near the two manufacturing to create a more flexible structure. We created a simulation study in AnyLogic where we examine the efficiency achievable by automated guided vehicles (AGVs) in a PI-based system. The results were compared based on the traditional and PI-based systems. Based on the simulation the inefficiency of the PI-based system is lower (by ~18%) at higher control event values. This allows achieving a more efficient, flexible, sustainable, and balanced operation.

1 Introduction

Achieving sustainable operations is currently one of the biggest challenges in both research and industry. In logistics, traditional transport, storing, and material handling methodologies cannot effectively increase individualization, demand, and quality. Physical Internet (PI, π) provides a new system, a vision presented as the future logistics system, breaking with all traditional methodologies, and building the new system on the model of the flow of information based on the Digital Internet data packet. PI specifies a holistic design based on the connectivity of the physical, digital, and operational worlds.

The Physical Internet's basic idea has already appeared in the literature in several different areas [1,2]. In recent years, there has been an increasing focus on exploring PI-based systems, with numerous studies on extralogistics systems [3], but only a few publications on intralogistics systems. Intralogistics processes provide the core system for companies and the focus of operational logistics activities. This is also a significant cost factor, so we consider it essential to examine the Physical Internet's feasibility in intralogistics systems as a forward-looking concept. The implementation of the Physical Internet requires a paradigm shift. The processes and tools must be examined from a new perspective. Like Industry 4.0, the focus is not only on the tools used but also on the way we are thinking. We determined the intralogistics transformation of each PI component. Without exception, all components have an internal system version. In the case of π-container, which plays a crucial role in extralogistics systems, we proposed using the Euro container, the so called KLT containers, which are already frequently used in industry. The abbreviation KLT comes from the German word *Kleinladungsträger*. The extralogistics and intralogistics versions of the π-container are shown in Figure 1. This gives the standard unit by which the operation can be based on PI.

Examining the Industry 4.0 tool applicability in PI systems, the simulation seems one of the most prominent [4]. As a reason for this, we also support the theoretical model with simulation in this research, with which we can obtain data-supported results at a much shorter time and a lower cost compared to experiments on real systems.

This research focuses on the intralogistics conversion of the Physical Internet. Using the intralogistics components identified in our previous research, we deal with restructuring a simpler factory into a Physical Internet-based system. We examine the five types of products' routes at the factory, which are moved between each station by automated guided vehicles (AGVs). We created the Physical Internet-based system's foundations by converting the raw material warehouse and semi-finished goods warehouse into PI-hubs and by creating virtual-hubs near the production lines. In the third chapter, we built a simulation model of the factory based on the new approach, in which we performed runs with different parameters. In the model, we examined the material handling tasks performed by AGVs, depending on the intervals at which vehicles receive tasks. We compared the efficiency, performance, and waiting times available with the traditional and PI-based systems. The purpose of the model is to present a possible PI-based factory design. Finally, in the fifth chapter, we define future research directions and summarize the article's results.

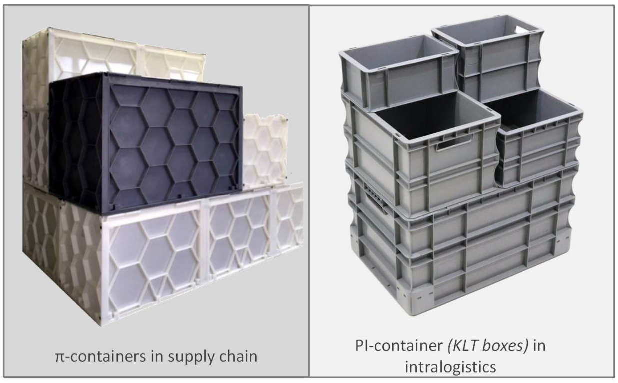

Figure 1 π-container in supply chain and in intralogistics [5]

2 Physical Internet in intralogistics

The Physical Internet concept provides a solution to world sustainability from a social, environmental, and economic perspective. It addresses the drivers' cowboy lifestyle, which socially improves the current situation [6]. Through open PI hubs in the logistics network, it aims to allow drivers to change vehicles in these centers to stay as close as possible to their homes. From an environmental point of view, it intends to improve the current system from several angles. The creation of the π-container as one of the essential elements of PI takes into account the standardization of transport, the traceability of information, and environmental factors [7,8].

Furthermore, through interconnectivity – mentioned as one of the cornerstones of PI [9] – PI wants to reduce a large amount of air shipping globally and shorten routes through cooperation between companies. From an economic point of view, a PI-based system also takes essential steps, as the cost factor affecting companies is also essential for sustainability. In addition, the implementation of platooning technology can bring additional savings in the field of road freight transport [10].

Another important component is the PI-hub. In the logistics network, we can distinguish between fixed and virtual PI hubs. In the case of a fixed PI-hub, we mean infrastructural elements similar to traditional exchanges, which in turn differ in their design and functional operation from those existing today. The main difference is that these PI-hubs are available to all PI-users, and their internal design is characterized by connectivity, flexibility, automation, and sustainability, as exemplified in [2,3]. Another type of PI hub, the virtual PI-hubs with no building and other infrastructure support, aims to make the network more flexible by supplementing fixed PI-hubs. Virtual PI-hubs define a meeting point that provides an additional opportunity to perform transhipments and material handling in the system [11].

When we talk about Physical Internet-based logistics networks, it is important to define what components are required. In our previous research, we first defined the components based on extralogistics systems [4], and then we also determined their intralogistics versions [5]. The components are summarized in Figure 2.

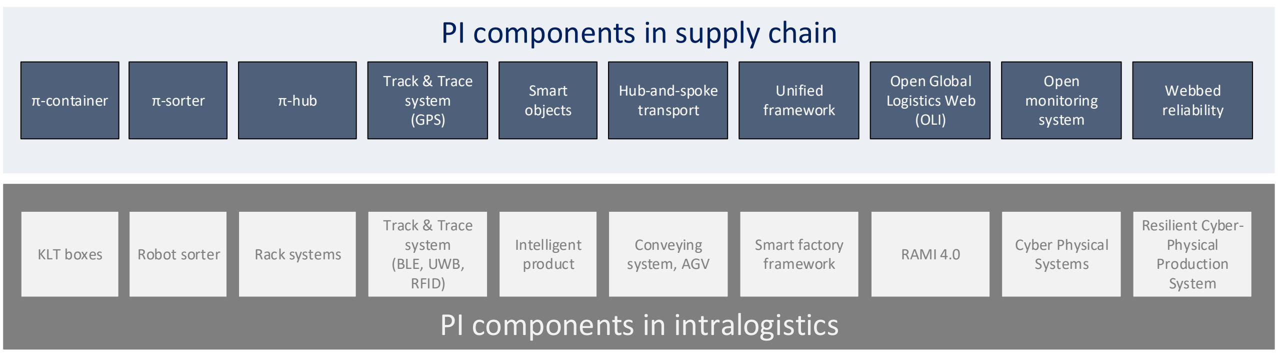

Figure 2 Physical Internet components in supply chain and intralogistics [10]

The components contain both physical elements and IT and control elements. For intralogistics systems, the physical elements include KLT boxes, robot sorters, pallet racking systems, and intelligent products and also include the conveyor system and AGV, the extralogistics conversion of hub-and-spoke. In the case of intralogistics, intelligent nodes play an important role for PI hubs, opening up new possibilities for local control of processes through centralized and decentralized concepts [12]. The IT components include the Track & Trace system, the

RAMI 4.0 for Industry 4.0 as a conversion of the open, global logistics web, and the Cyber-Physical Systems. Control components include the smart factory framework and the resilient Cyber-Physical Production System [5].

Ray Y. Zhong (2016) introduces a PI-based production management system (PIM2S), focusing on software perspectives such as system architecture and key services. He proposed a framework where real-time data from factories is collected using RFID technology. They also develop an interface service based on a middleware software concept that allows communicating with other systems through a standardized interface. Through a case study, they report on how PIM2S improves the tracking of real-time planning and scheduling [13]. In a similar approach, Ray Y. Zhong et al. (2016) proposed a PI-based manufacturing execution system (PIMES) for an intelligent workshop. A case study was conducted on a typical Mass-Customized company. The problem that indicated the implementation of PI is the frequent insertion and deletion of orders into production, which is difficult to control and follow even with the existence of an enterprise resource planning (ERP) system. By integrating PI, they create an omnipresent production environment. It has been shown that PI can support real-time decision making, automated statistics, and visualized production control and management [14].

Ray Y. Zhong et al. (2014) presented a PI-based shopfloor logistics management based on RFID-enabled Big Data methodology. They demonstrate the PI-based system's operation through a real manufacturing example, providing a basis for other RFID-compliant companies to build a forward-looking system. Methods for evaluating some KPI indicators are presented using the Big Data methodology. Their research draws attention to the widespread use of the Physical Internet and further explores its potential, highlighting real-time data-driven decision support [15]. Their previous research is developing a Big Data Analytics architecture based on information collected by RFID on the shop floor. One of the key basic PI elements, the π-container, has been expanded into a smart pallet [16].

An article by Lin I.-C. and Chen C.-Y. (2018) draws attention to the problem that currently all manufacturers produce a Physical Internet device with a unique specification, and compatibility between individual brands is very low. As a result, they present a platform system through a case study. This included an automatic product identification system, a tracking system, a finished product scanning, and packaging system, and an electronic shelf system. Expected benefits after deployment include reduced time and labor costs (~35% reduction), easier inventory and tracking through a smart shelving system, and improved machine capacity [17].

In [18], the authors focus on the production schedule as a classical combinatorial NP-difficult optimization problem and transform the traditional factory into a PI-based manufacturing system. The production schedule is divided into passive and initiating schedules depending on who initiates and directs the related decisions. They detailed that the technologies provided by Industry 4.0, such as IoT (Internet of Things), CPS (Cyber-physical system), cloud, and Big Data, provide the foundation for implementing the observation, computation, and service required for a PI-based system. The new system is called π-manufacturing system (π-MS). The π-MS system, with the new production environment, brings changes in the management of production processes and resources. It aims to implement intelligent tracking and precise identification. Interconnectivity, communication, standard protocols, and track&trace system as the Physical Internet's basic pillars also appear here. They compare their operations with current advanced manufacturing systems such as flexible manufacturing systems (FMS), agile manufacturing systems (AMS), and intelligent manufacturing systems (IMS). By comparison, they found that π-MS is more transparent, agile, flexible, and robust. The comparison is organized in Table 1. The π-MS implements the technological foundations of an intelligent, dynamic, interconnected, and flexible manufacturing environment.

Table 1 Comparison between π-MS and traditional manufacturing system [18]

	π-MS	**Traditional manufacturing system**
Production-driven pattern	Information-driven pattern	Energy-driven pattern
Response mode	Initiative respone	Passive respone
Production process control	Intensive pattern	Extensive pattern
Management style	Tranparent management	Black box management
Organizational structure	Flat structure	Hierarchical structure
Management dimension	Multi-dimensional (mesh network)	Two-dimension (manager and managed)
Decision-making approach	Autonomous interaction	Administrative assignment

In this paper, we present a simulation study on the possibility of using the Physical Internet in intralogistics. Based on the results presented in [15], we track with RFID all units in the production system. By continuously tracking the KLT boxes, we use location identification for planning and timestamp data for subsequent analyses. Like the π-MS presented in [17], we are developing new processes for resource management to implement a more efficient, agile, and flexible system with the new manufacturing environment. In the simulation, we examine the material handling tasks performed by AGVs. We then compare the traditional and PI-based manufacturing structures. The results of the comparison are detailed in the following sections.

3 Methods

In this section, we describe the PI-based manufacturing processes. As there are various scenarios on possible factory designs, we tried to focus on a basic layout to show the PI system's general applicability. The fundamental goal of the new structure is to break with the traditional operating logic (*TRAD*) and actualize an innovative manufacturing network system based on the Physical Internet (*PIHUB*).

3.1 Structure of the proposed model

In the model, we examine a simple manufacturing process with five different product routes. The basic idea comes from [8], on which Figure 3 is based. There are nine different transport relations in the traditional system depicted by the black arrows, each representing a different material handling activity. Traditional operating vehicles only transport between dedicated locations always on one route.

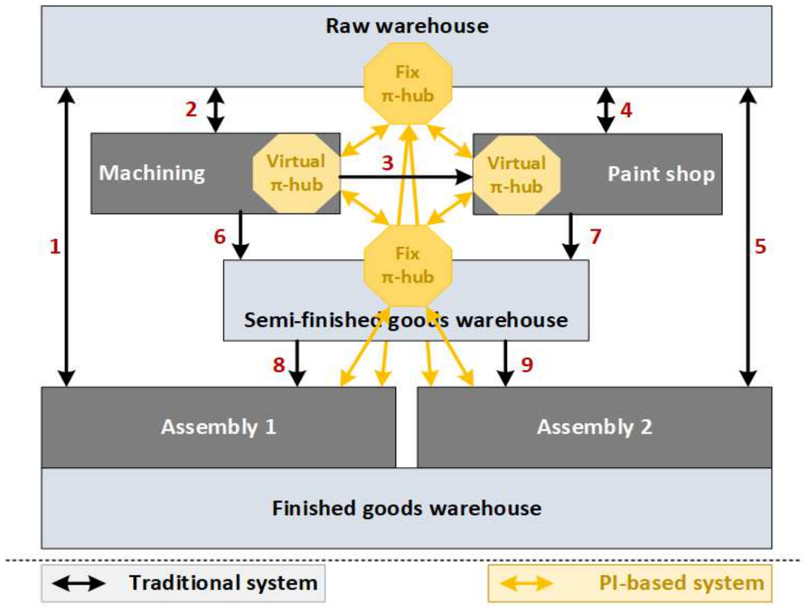

Figure 3 Simple factory design with PI implementation based on [5]

In contrast, the PI concept is to use all vehicles on all routes between all points. In Figure 2, PI implementation is also shown by the yellow arrows. Raw warehouse and semi-finished goods warehouse are transformed into fixed π-hubs so that every PI-user (vehicle) can access rack stores. Next to the machining area and the paint shop, we create virtual π-hubs. Thus, the KLT exchange can be executed similarly to an extralogistics PI system. Due to small distances in intralogistics, the locations of virtual π-hubs do not change in this factory. Unlike fixed π-hubs, virtual π-hubs do not have an infrastructural design like rack storage systems as fewer KLTs are in these areas than fixed π-hubs [5,11]. We need to model the flow of KLTs full of parts, and we also need to pay attention to the reverse logistics of the empty crates. This is the reason most routes are bidirectional. Routes (3) and (6)…(9) only flow in just one direction because only the raw warehouse expects empty KLT crates.

Creating a simulation environment of the presented model was essential for further examinations. The factory built in AnyLogic® Version 8.7.2 is shown in Figure 4. The coloured lines illustrate the five product routes. The gray and yellow ones show the two materials directly supplied from the raw warehouse to Assembly 1 and 2. The red and blue lines represent the first machined or painted materials which then are stored in the Semi-finished goods warehouse before being transported to Assembly 1 and 2. Green is the most complicated route in which the product is first machined, then painted after that stored in the Semi-finished goods warehouse and carried to Assembly 2. Nine AGVs carry out the transport tasks.

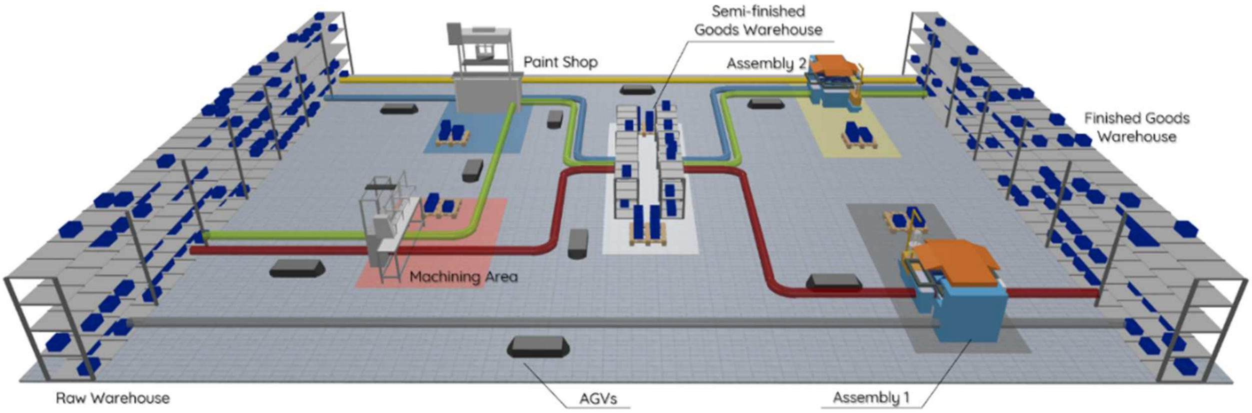

Figure 4 The 3D simulation model of the example factory

The AGVs are path-guided vehicles meaning they can only use straight paths similar to the lines shown in Figure 3. The usual load of an AGV in intralogistics systems is one EUR1 pallet. The modeled AGVs can carry four standard KLTs (400x600x200 mm) in one layer. Four layers can be stacked, resulting in a total of sixteen KLTs on one AGV. As the vehicles move surrounded by workers for safety reasons, the speed of the AGVs is 0.8 m/s [19]. The main inputs of the simulation are the time intervals that each KLT arrives in the raw warehouse. The KLTs are generated based on normal distribution taking into account the stochasticity of factory processes (Table 2). The time horizon of the simulation is 16 hours, starting from zero minutes to 960 minutes. Depending on the input parameters given according to Table 2, the minimum control event value is 5 minutes since KLTs arrive in the system average every 4.2 minutes. However, the maximum control time was set at 1 hour to ensure continuous operation of the factory. Accordingly, the generated KLTs wait for departure as every AGV launch will take action across a range of values from 5 min to 60 min.

Table 2 Time intervals between KLTs

Product type	Mean	Deviation
Product 1 (Gray)	3 min	1 min
Product 2 (Red)	4 min	2 min
Product 3 (Green)	6 min	1 min
Product 4 (Blue)	5 min	2 min
Product 5 (Yellow)	3 min	3 min

3.2 Solution methodology

Discrete Event Simulation (DES) is the most common method of modeling microsystems such as intralogistics networks. A sequence of events models the process in which the observed passive entities (in our case, the KLT compartments) flow in a predetermined order. This simulation method is often used alongside Agent-Based Modeling (ABM), which consists of active objects such as AGVs. These active objects can communicate with each other and can interact with the environment. We can combine the two simulation methods and build automatic systems. We used the Process Modeling Library (version 8.0.5) and the Material Handling Library (version 8.3.0) of the AnyLogic simulation software to create the traditional and the PI-based intralogistics system. We first present the traditional version structure and then describe the changes we made to develop the PI-based version.

There are three agents in the model. The first one is the KLT, the second one is the UNIT which contains the given number of KLTs transported together, and the third one is the AGV which transports the units. Each of the five product routes has a Source object which generates the KLTs at the given time intervals based on Table 2. To initialize the model, we insert KLTs from all product type at the beginning of the simulation. After each source object, we insert a queue where the created KLTs are waiting for delivery. The queue objects do not have capacity limitations. As mentioned, the KLTs wait until the AGV launch. Until then, the process is held back by a Hold object. The hold objects are initially blocked and set to allow through a specified number of agents before blocking the process again. A Batch object follows the hold objects. This object is responsible for arranging the given number of KLTs into the new UNIT agent.

After batching the KLTs, the MoveByTransporter block transports the unit to the specified destination where the unit is unbatched by the UnBatch object. One Transporter Fleet is dedicated for each relation (9 fleets each with one AGV), and the vehicles can only transport between the predefined locations. In case it is the final destination of the KLTs, they exit the model by a Sink object. Otherwise, at the assembly lines, machining, and painting areas, the KLTs wait in a queue before entering the Delay objects. After the delay, a Split object creates a new KLT agent representing the crate full of finished or semi-finished goods. This way both the empty and the full crates stay in the model. These full crates exit from the model at the assembly lines, but from the machining and painting areas, they enter a queue object, and from there, they are transported to the next station. The empty KLTs continue their path into a queue so the AGVs can transport them back them to the raw warehouse. These forwarding and reverse transports are modeled by the same process already explained, beginning with the queue object and finishing with the sink object. Figure 5 shows the first route (from the raw warehouse to assembly 1 and back). As the transporting method is the same for all routes we used a flowchart block that is equivalent to a function in which we only need to change each route's parameters. This flowchart block is shown in Figure 6.

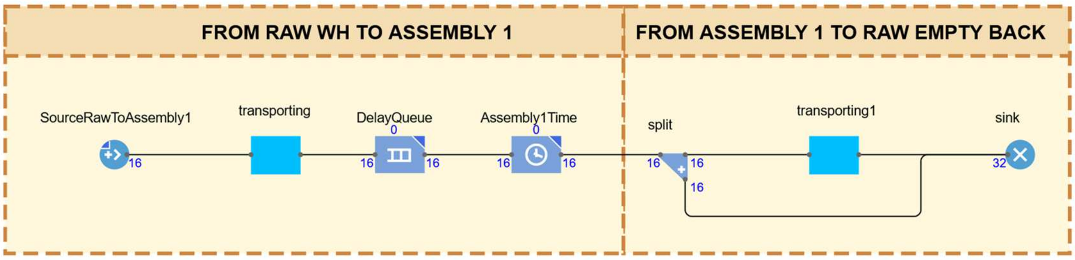

Figure 5 AnyLogic flowchart of first route

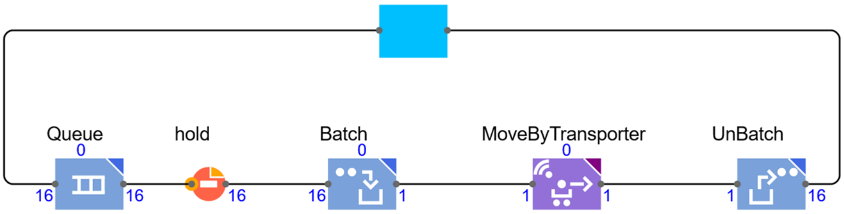

Figure 6 Transporting flowchart block

A control event guide the *hold* object. The control event occurs in the first run every 5 minutes, in the second run every 10 minutes, in the third run every 15 minutes, and so on up to 60 minutes. The event logs the number of agents waiting in all queues at the moment. The model examines 13 waiting lines. Four from the raw warehouse to the machining, painting, and the two assembly areas and also four for the empty KLTs from these areas back to the raw warehouse. One from the machining to the painting area and two from the machining and painting areas to the semi-finished warehouse. It is unnecessary to return the empty KLT from a semi-finished warehouse, either between the machining or painting areas. The last two lines are from the semi-finished warehouse to the assembly line 1 and 2. For each relation, the software algorithm compares the number of KLTs waiting for transport, if there are any. For instance, on the first route where the KLTs move from the raw warehouse to assembly 1 and then the empty KLTs are transported back, the event will unblock the direction with more KLTs waiting in line. If there is no KLT waiting, then this AGV will not be launched. If a route is not bidirectional, then the waiting line is compared to zero. To execute the transportation with the corresponding number of KLTs, before unblocking the hold objects, we need to set the unit's batch size to be the same amount as the number of agents allowed through the hold object. If the chosen direction has less than sixteen KLTs in the queue (capacity of the AGV), we set the hold and batch objects' parameters to the number of the waiting KLTs. Otherwise, we set it to sixteen. This method runs for every relation launching the AGVs for each transportation. The model stores the size of the batches in an external database. After AGVs finished the transport, they stay where they are. In this scenario, on a relation, only one AGV transports in only one direction per launch. It means that if a bidirectional relation (e.g., Raw WH to Assembly 1 and back) has KLTs waiting on both sides, and a not bidirectional relation (e.g., Semi-finished WH to Assembly 1) has zero KLTs, then at least one AGV will be unassigned.

We do not modify the model's main structure in the PI-based system but change two fundamental logic. One Transporter Fleet executes the transports with 9 AGVs. AGVs do not only travel in fixed connections so that all vehicles can travel from any location. The control event also operates differently. Instead of checking the relations separately, it lists the thirteen queue lines in a descending order based on the number of KLTs waiting. As there are nine transporters, they will transport the first nine queues with the highest number of KLTs. The model unblocks the "hold" objects, and the batch sizes are set by the same method as explained before. When a transporter does not have a task on one path, it can move to another relation. The main difference is shown in Figure 7.

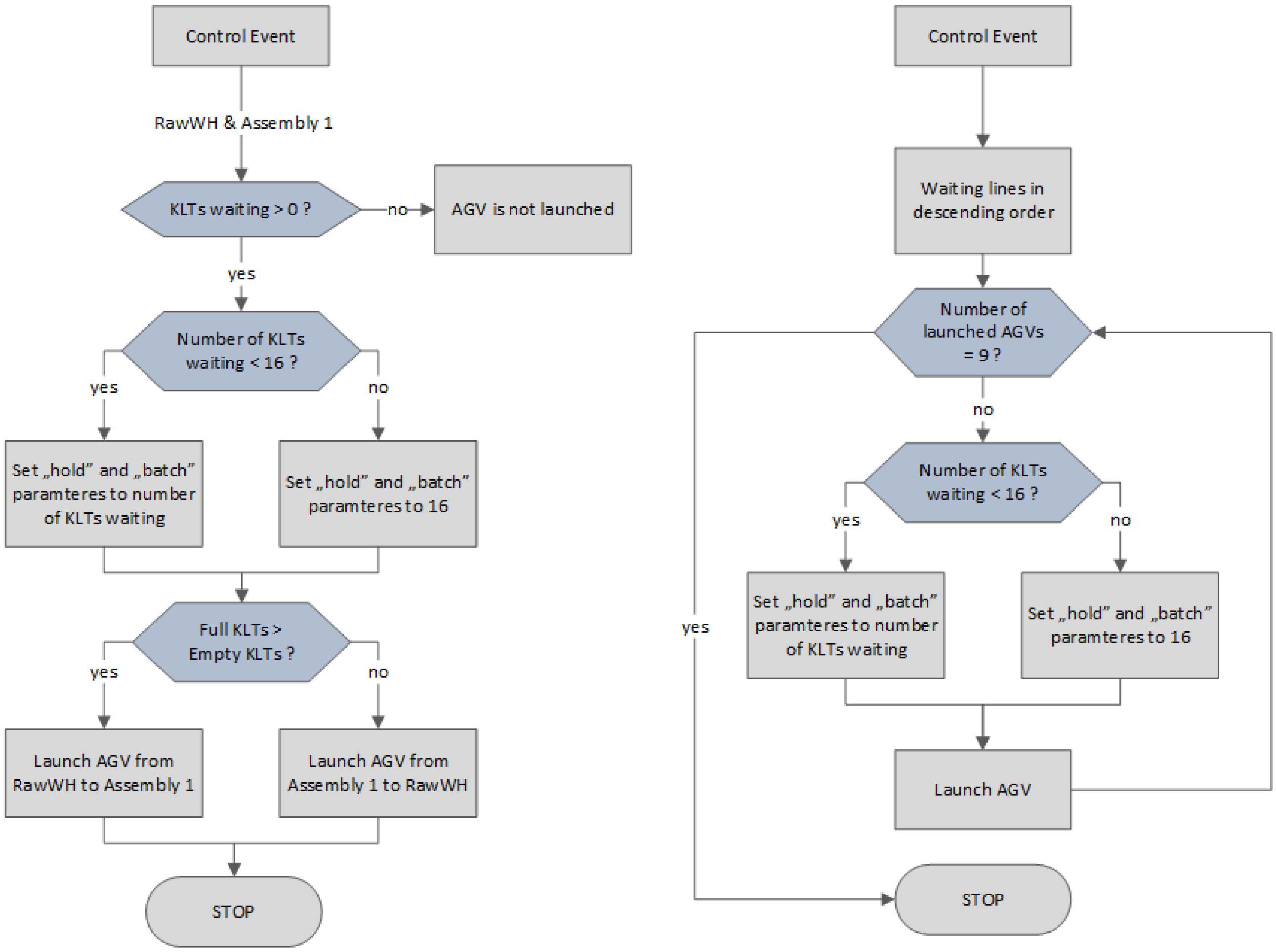

Figure 7 Proccess Chain of traditional (left) and PI-based (right) system

4 Results and discussion

In this chapter, we detail the simulation results of the presented Physical Internet-based model. In the simulation studies, the input data for the arrival of KLTs were always the same, according to Table 2. We changed the event's value that controls the scheduling of AGVs from 5 min to 60 min, which declared how often AGVs receive new tasks. For each different interval, we run the simulation five times for 16 hours on both models. Thus, resulting a total of 12 cases, we performed five runs in each case for the given structure, so we performed a total of 120 simulations. In the study, we compared the two algorithms (traditional and PI-based) presented in Chapter 3.2. In comparison, we determine some Key Performance Indicators (KPIs) based on [20] and [10]. We evaluate the results from two perspectives: we analyze the AGVs and KLTs. For the formulas used for KPIs, Table 3 shows the general notations compiled.

Table 3 Mathematical notation

Parameter	Description
V	set of vehicles (AGVs)
N	set of KLTs
$s_k(i,j)$	length of the kth transport route between points (i,j)
$C_{free,k}$	free capacity in loading units during the kth transport task
C_k	capacity in loading units during the kth transport task
$\Delta t\ (waiting)$	length of a KLT wait time until an AGV picks up to move
M_{KLT}	total number of KLTs moved between examined locations
V_{busy}	total time an AGV was busy
t_{shift}	time of the shift used in the simulation (16 hour)

First, we analyze the KPIs for AGVs. The first indicator examined is ineffectiveness, which can be calculated based on [10] as follows:

$$Ineffectiveness = \sum_{k=1}^{V} \frac{c_{free,k} \cdot s_k(i,j)}{C_k \cdot s_k(i,j)} (\%) \qquad (1)$$

We determined the product of the capacity left free and the distance traveled by the AGVs. The value obtained was then divided by the theoretical worst case, i.e., the product of the empty AGV and the same path. We calculate this for each movement of each AGV for both traditional and PI-based manufacturing structures. The value of inefficiency can be between 0% and 100%. The ineffectiveness values of the runs from 5 min to 60 min are shown in Figure 8.

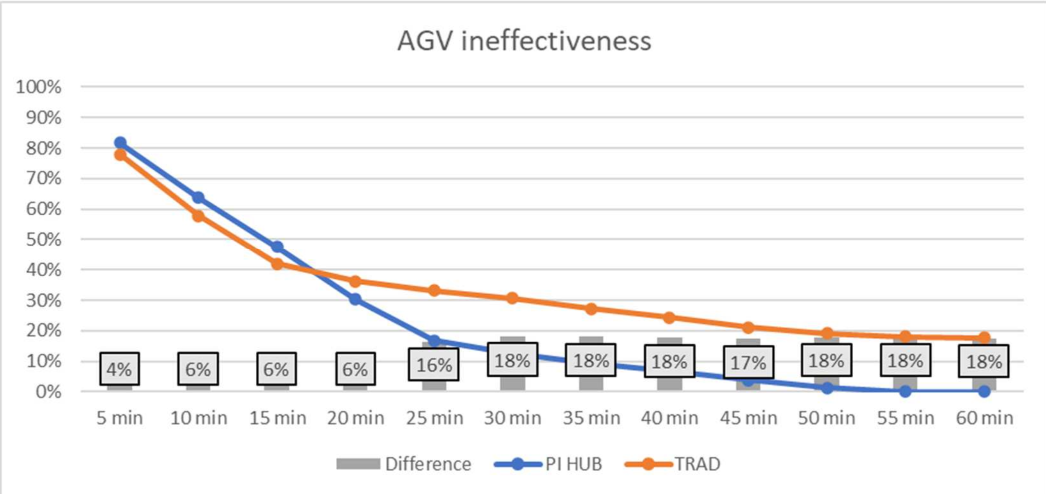

Figure 8 Ineffectiveness of AGVs for PI-based and traditional structures

Based on ineffectiveness, the lower its value, the better the system works. Accordingly, we can see that PI-based manufacturing can operate more efficiently in all cases. The initial high value is related to the normal distribution parameters used for KLT generation, as KLTs arrive in the system too infrequently for a 5,10,15-minute start. At higher event times, enough KLT can already flow in the system for a PI-based system to operate efficiently. The less frequently (at longer time intervals) AGVs are given a task, the inefficiency decreases. In the figure, the gray bars show the degree of difference between PI-based and traditional systems.

The next examined indicator is the material handling performance, which was calculated as follows:

$$Performance = \sum_{l=1}^{N} \frac{M_{KLT} \cdot s_k(i,j)}{t_{shift}} \left(\frac{KLT \cdot meter}{hour}\right) \qquad (2)$$

According to the formula, we multiplied the distance traveled during movement by the number of pieces moved for each unit. The product was then divided by the length of the study period, which was 16 hours. We calculate this for each KLT moved. The results for the cases studied from 5 minutes to 60 minutes are illustrated in Figure 8.

Based on Figure 9, there is no significant difference in material handling performance between the two structures (*PIHUB* or *TRAD*). Except for low control event values (5,10,15 minutes), the PI-based system achieved higher material handling performance. There is a decrease in material handling performance for larger control events. With a higher control value, AGVs deliver KLTs less often. Although the utilization of the AGV increases, as shown in Figure 8, it cannot result in higher performance due to the maximum capacity limiting condition (16 KLTs/AGV).

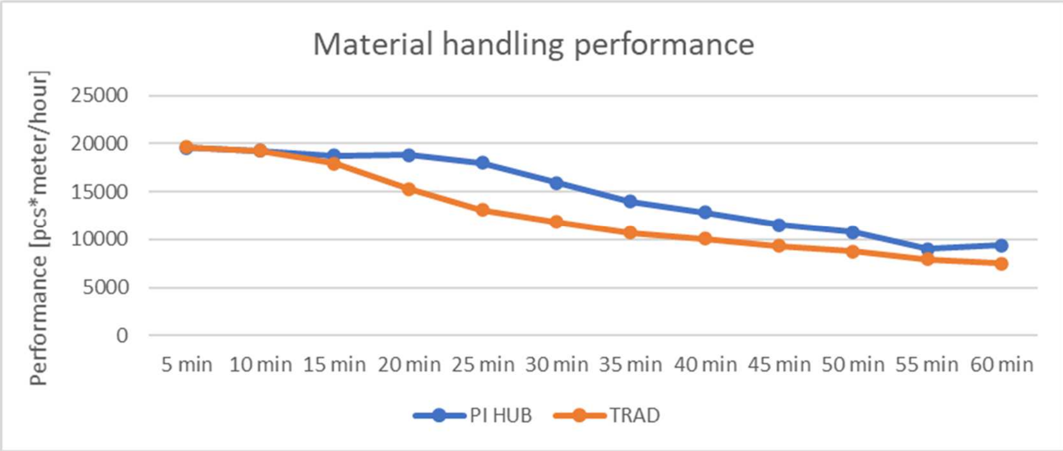

Figure 9 Material handling performance of AGVs for PI-based and traditional structures

The next two parameters analyze the KLTs. The first illustrates the intensity values for each relation, which were calculated as follows:

$$Intensity = \frac{M_{KLT}}{t_{shift}}\left(\frac{KLT}{hour}\right) \quad (3)$$

We divided the total number of KLTs delivered in the examined time horizon by the value of the examined time horizon. The result obtained is shown in Figure 10.

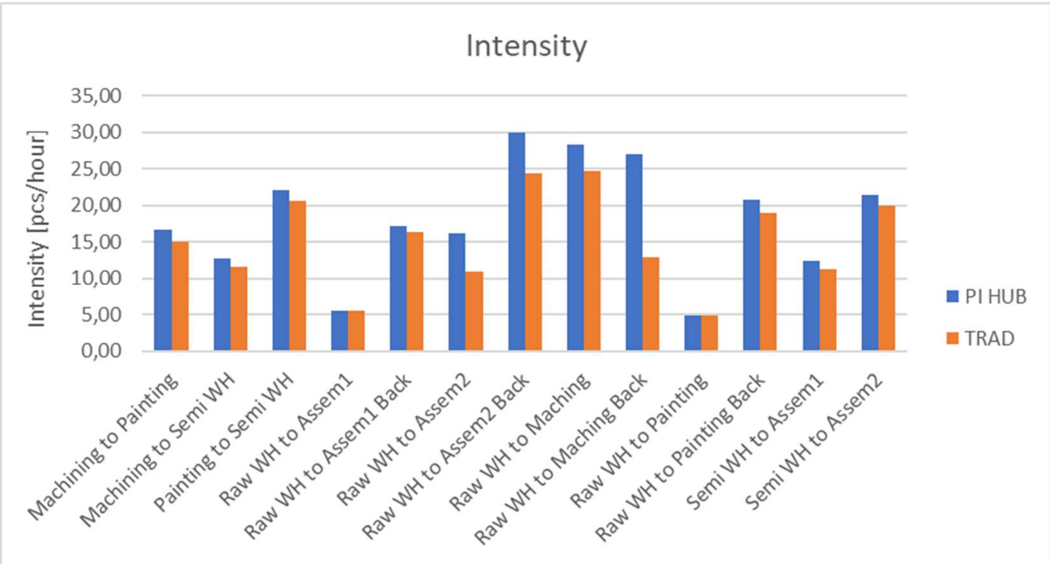

Figure 10 Intensity for each relation

Stochastic processes induce the discrepancies shown in Figure 10. The purpose of this diagram is to illustrate the significant intensity differences that appear in different directions. In the case of a traditional factory structure, where the AGV was assigned to a given direction, the AGVs cannot compensate for the hectic process. In the Physical Internet-based system, where, in addition to making KLTs intelligent, the PI hubs create an open system and flexibility. With this novel PI-based system, handling the differences (shown in Figure 9) is less problematic. AGVs manage the entire system together to decide which next delivery task to perform.

Finally, we examined the waiting time of the KLTs, the time that the KLT waits for the AGV to complete the moving task. The calculation of the waiting time was performed as follows:

$$Waiting\ time = \frac{\sum_{i=1}^{N} \Delta t\,(waiting)}{N}\ (min) \quad (4)$$

For the given system, we determined the average waiting time. Based on the formula, we determine the waiting time for each KLT, and after summarizing, we divided it by the number of KLT boxes (Figure 11).

Figure 11 Waiting time of KLTs for PI-based and traditional structures

We can achieve slightly better values in the traditional system in waiting time, so the KLT has to wait less to move as soon as an AGV starts to pick up for it. The goal of the PI-based system is sustainability, which in this case can be related to balanced operation. In a PI-based system, to minimize the number of empty turns, the KLT must wait longer for larger volumes to accumulate. In the traditional system, it is not decided at the system level which unit should be delivered by the AGVs. According to the simulations, on average ~37% more KLTs remain in the traditional system, so the conventional operation is on average 37% more congested. Also, in the traditional case, the required distance traveled is usually shorter, as the AGV only travels back and forth on one road section. Therefore we can get a slightly longer waiting time for a PI-based system to achieve a more sustainable and balanced operation.

Based on the results, we can say that the Physical Internet integration is also worthwhile in terms of intralogistics systems. We expected the available improvement to be lower than an extralogistics system, but the new structure and mindset may offer many new opportunities compared to traditional systems. The creation of a PI-based intralogistics system supports the achievement of the sustainability, flexibility, and higher efficiency needed for the future's challenges.

5 Conclusion

The Physical Internet as a future logistics system model is gaining more and more interest among academics. Although publications mostly approach the supply chain side, studies on intralogistics applicability are beginning to occur. In our opinion, the integration of the Physical Internet into intralogistics systems is useful. In this article, we created an innovative PI-based factory structure. The warehouses were converted to PI-hubs, and virtual PI hubs were placed near the two manufacturing elements (machining and painting) to create a more flexible structure. The π-containers were realized with KLTs, and AGVs performed movements. AGVs are assigned tasks driven by a control event. We created the model in an AnyLogic simulation environment. During the simulation runs, we examined the results obtained by changing the control event's time value from 5 min to 60 min. The results were compared based on the traditional and PI-based systems. During the evaluation, we determined the values of ineffectiveness, performance, intensity, and waiting time. In the case of ineffectiveness, the maximum value is 100%, in the case of the other parameters the maximum cannot be determined, their value depends on the generated input data and the operating logic. The main result is that the PI-based system's inefficiency is lower at higher control events to achieve more efficient and flexible operation. Furthermore, in the case of waiting time, the traditional system provides better operation, but the system will be less sustainable and balanced.

Further research and development are also needed, such as examining the functional operation of the appearing warehouse elements. By creating a more accurate schedule, the system could also be further developed, including emerging technologies such as Big data or machine learning.

References

[1] PAN, S., NIGRELLI, M., BALLOT, E., SARRAJ, R., YANG, Y.: Perspectives of inventory control models in the Physical Internet: A simulation study, *Computers & Industrial Engineering*, Vol., 84, pp. 122-132, 2015. doi:10.1016/j.cie.2014.11.027

[2] MELLER, R.D., MONTREUIL, B., THIVIERGE, C., MONTREIUL, Z.: *Functional Design of Physical*

Internet Facilities: A Road-Based Transit Center, Computer Science, 2010.

[3] MONTREUIL, B., MELLER, R.D., THIVIERGE, C., MONTREUIL, Z.: *Functional Design of Physical Internet Facilities: A Road-Rail Hub*, Progress in Material Handling Research, 2012.

[4] PUSKÁS, E., BOHÁCS, G.: Physical Internet – a Novel Application Area for Industry 4.0., *International Journal of Engineering and Management Sciences*, Vol. 4, No. 1, pp. 152-161, 2019. doi:10.21791/IJEMS.2019.1.19

[5] PUSKÁS, E., BOHÁCS, G.: Intralogistics Conversion of the Physical Internet, *LISS 2020 Proceedings of the 10th International Conference on Logistics, Informatics and Service Sciences*, Vol. 8, 2021. doi:10.1007/978-981-33-4359-7

[6] MONTREUIL, B.: Toward a Physical Internet: meeting the global logistics sustainability grand challenge, *Logistics Research*, Vol. 3, pp. 71-87, 2011. doi:10.1007/s12159-011-0045-x

[7] LANDSCHÜTZER, C., JODIN, D., EHRENTRAUT, F.: *Modular Boxes for the Physical Internet –Technical Aspects*, International Scientific Symposium on Logistics, 2014.

[8] LANDSCHÜTZER, C., EHRENTRAUT, F., JODIN, D.: Containers for the Physical Internet: requirements and engineering design related to FMCG logistics, *Logistics Research*, Vol. 8., pp. 1-22, 2015. doi.10.1007/s12159-015-0126-3

[9] MONTREUIL, B., MELLER, R.D., BALLOT, E.: Physical Internet Foundations, *Service Orientation in Holonic and Multi Agent Manufacturing and Robotics*, Vol. 472, 2013. doi:10.1007/978-3-642-35852-4_10

[10] PUSKÁS, E., BUDAI, Á., BOHÁCS, G.: Optimization of a Physical Internet based supply chain using reinforcement learning, *European Transport Research Review*, Vol. 12., No. 1, 2020. doi:10.1186/s12544-020-00437-3

[11] PUSKÁS, E., BOHÁCS, G.: Concepting freight holding problems for platoons in Physical Internet systems, *Acta logistica*, Vol. 6, No. 1, pp. 19-27, 2019. doi:10.22306/al.v6i1.114

[12] BOHÁCS, G., GÁSPÁR, D., KÁNYA, D.: Conception an intelligens node architecture for intralogistics, *Acta logistica*, Vol. 5., No. 2., pp. 31-37, 2018. doi:10.22306/al.v5i2.82

[13] ZHONG, R.: Design and Development of a Physical Internet-Enabled Smart Factory for Discrete Manufacturing, *Proceedings of the 22nd International Conference on Industrial Engineering and Engineering Management*, pp. 549-556, 2015. doi:10.2991/978-94-6239-180-2_53

[14] ZHONG, R., HUAJUN, G., YU, C., LU, S.: Physical Internet-Enabled Manufacturing Execution System for Intelligent Workshop Production, *International Journal of Signal Processing,* Vol. 9, No. 6, pp. 121-132, 2016. doi:10.14257/ijsip.2016.9.6.11

[15] ZHONG, R., HUANG, G., LAN, S.: *Shopfloor Logistics Management using RFID-enabled Big Data under Physical Internet*, 1st international Physical Internet Conference, Québec City, Canada, 2014.

[16] ZHONG, R., XU, C., CHEN, C., HUANG, G.: Big Data Analytics for Physical Internet-based intelligent manufacturing shop floors, *International Journal of Production Research*, Vol. 55, No. 9, pp. 2610-2621, 2015. doi:10.1080/00207543.2015.1086037

[17] LIN, I.-C., CHENG, C.-Y.: Case study of physical internet for improving efficiency in solar cell industry, *Journal of Ambient Intelligence and Humanized Computing*, Vol. 9, pp. 285-294, 2018. doi:10.1007/s12652-016-0355-6

[18] WANG, J.Q., FAN, Q.Q., YAN, F.Y., ZHANG, Y.F., SUN, S.D.: Research on initiative scheduling mode for a physical internet-based manufacturing system, *The International Journal of Advanced Manufacturing Technology*, Vol. 84, pp. 47-58, 2016. doi:10.1007/s00170-015-7915-3

[19] TU, J. C., QIAN, X.M., LOU, P.H.: Application research on AGV case: automated electricity meter verification shop floor, *Industrial Robot: An International Journal*, Vol. 44, No. 4, pp. 492-500, 2017. doi:10.1108/ir-11-2016-0285

[20] STAUDT, F., MASCOLO, M. D., ALPAN, G., RODRIQUEZ, C.: Warehouse performance measurement: classification and mathematical expressions of indicators, *ILS 2014 - 5th International Conference Information Systems, Logistics and Supply Chain*, Breda, Netherlands, 2014. doi:10.13140/2.1.4214.7207

Review process

Single-blind peer review process.