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Physical Internet based Hyperconnected Logistics Platform Enabling Heavy-Duty Machinery Sharing in the Composting Industry: A Simulation-Based Scenario Investigation

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Abstract:

Composting plants face significant challenges in meeting increasing quality standards and production rates due to the high costs of essential composting machinery. To address these issues, a Physical Internet based Hyperconnected Logistic Platform for Heavy-Duty Machinery (HLHD) has been proposed. The HLHD system enables composting plant operators to share expensive machinery between plants, allowing for improved efficiency, cost-effectiveness, and enhanced compost production quality.

The HLHD operates by transporting composting machinery between designated hubs and participating composting plants, where they perform their specific tasks during the composting process. To evaluate the efficacy of the proposed HLHD system, a simulation-based study of three distinct scenarios has been conducted.

The first scenario focused on small and medium-sized composting facilities, providing an accessible and cost-effective solution for smaller facilities. In the second scenario, all composting facilities participate in the HLHD to an equal extent, while the third scenario assumed that big composting plants already own the necessary equipment. However, since the utilization of machinery at these large farms is generally low, they participate in the HLHD by serving as hubs once their machinery is idle.

Overall, the HLHD system shows great potential in addressing the challenges faced by composting plants. The proposed system can lead to improved resource utilization, enhanced efficiency, and reduced costs, ultimately leading to better quality compost production.

Keywords: *Physical Internet, Hyperconnected logistic, Heavy-Duty Machinery, Simulation, Composting.*

Conference Topic(s): *autonomous systems and logistics operations (robotic process automation, autonomous transport/drones/AGVs/swarms) business models & use cases; communication, networks; logistics and supply networks; PI impacts; PI implementation; PI modelling and simulation; vehicles and transshipment technologies.*

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

1 Introduction

The vision of the Physical Internet is to achieve a globally accessible logistics system characterized by a combination of physical, digital, and operational interconnections enabled through the utilization of encapsulation, interfaces, and protocols. The aim is to create an ever-evolving system that thrives on technological, infrastructural, and business advancements [1], [2]. One of the areas of the PI vision is the establishment of hyperconnected networks in various fields. The approach of the PI Vision is thereby universal and not limited to a specific industry [3], [4]. Since this study deals with the organic waste industry, more specifically with composting, a brief introduction to the state of the art in Central Europe is given. The organic waste recycling and processing sector is a fast-growing industry in Europe. In the past 20 years there has been a rapid increase of over 80% in this industry, with a volume of over 40 million tonnes of compost processed within the EU in 2023 [5]. As the EU introduces regulations requiring the compulsory treatment of organic waste for member states, it is expected that this trend will continue to grow in the future [6]. The ever-increasing pace of technological advancement is driving the waste management sector to explore and implement innovative approaches to cope with the challenges. In response to this demand, significant efforts are underway in the research and development of cutting-edge technologies that can address the complex issues of the sector. The aim is to develop new methods and tools that are more efficient, sustainable, and cost-effective, while also reducing the environmental impact of waste management activities. [7]–[11]

Therefore, before addressing the PI vision's adaptation for this sector, a brief overview should be given. Composting can hereby be defined as an intricate aerobic process involving the degradation of organic materials or biogenic waste from separate collection under controlled environmental conditions. This process takes place in a composting plant, an anaerobic biological treatment facility that utilizes biological waste as feedstock, and relies on a diverse range of microorganisms for its successful execution. The produced compost is the outcome of largely completed aerobic decomposition, characterized by specific quality parameters that satisfy regulatory requirements for usage and marketability. This nutrient-rich end-product can be employed in numerous ways, including as a natural fertilizer and a soil enhancer for agriculture purposes [12], [13]. The widely used industrial technique for the production of compost is the compost windrow process, also known as "open composting". This process involves placing the organic waste material in long lanes, typically measuring between 1.2 to 1.5 meters in height and 2.5 to 3 meters in width, depending on the specific composting facility. In order to facilitate the proper progression of the biological process of composting, it is necessary that the compost windrows are regularly turned, a task which is executed by specially designed machines known as compost turners. The frequency of turning is determined by several factors, including the nature of the organic waste, ambient temperature and humidity, and the desired end-product quality. However, it is generally accepted that the turning should not occur less than three times per week in order to maintain high quality standards. The utilization of open windrow composting technology has gained significant recognition and establishment throughout Central Europe, with Austria exemplifying the adoption of this method through the establishment of numerous smaller-scale, regionally-targeted composting facilities. [14]

As the basic principles and techniques of composting are understood, it becomes clear that the underlying principles and concepts of the Physical Internet can be extended and applied to this field as well. Considering the robust growth of the composting industry, there exists an urgent and pressing need to explore and leverage the advantages and opportunities offered by the Physical Internet. It is evident that there has been a lack of research in this particular area, with only a restricted number of studies conducted thus far. It is worth highlighting the contributions made by Larsen, Hansson and Lagerkvist in this field, who have delved into the subject of farm machinery sharing within the agricultural sector of Northern Europe. Through the utilization of survey methods, it was discovered that the practice of sharing agricultural machinery among farmers resulted in a boost in operational efficiency [15], [16]. Despite the substantial amount of research conducted on existing systems, the fundamental concept of an interconnected network, as envisioned by the Physical Internet Vision, has yet to be considered or explored within these studies. In other words, previous works have solely focused on the analysis of established systems, with little to no attention directed towards the theoretical framework proposed by the Physical Internet Vision. Consequently, there is a critical gap in the current understanding of the potential implications and benefits of interconnected network models.[17]

Therefore, this paper proposes and investigates the potential of a Hyperconnected Logistic platform for Heavy-Duty machinery (HLHD) for compost production that leverages Physical Internet (PI) concepts and principles. As synthesized in Figure 1, we introduce the HLHD concept, develop specific deployment scenarios, and investigate through a simulation-based experiment their relative performance to enable the sharing of composting machines under various constraints. Through this approach, we aim to establish a comprehensive understanding of the potential of the HLHD platform and its practical implications for the composting industry.

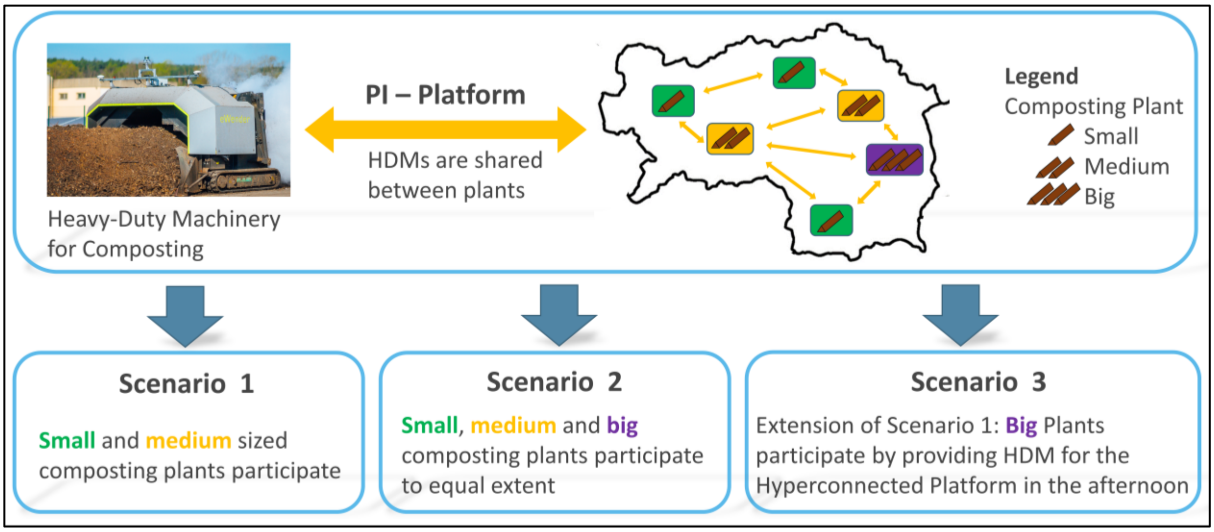


Figure 1: Proposed Physical Internet based hyperconnected logistics platform for heavy-duty machinery (HLHD)

2 Methods and Tools

As a result of the significant costs associated with the acquisition and operation of essential machinery, many composting plants are unable to procure the necessary equipment required to compete with the ever-increasing composting rate and quality standards. The objective of implementing a Physical Internet based Hyperconnected Logistic Platform (HLHD) is to mitigate this challenge by providing plant operators with the option to share the expensive composting machines among themselves. The proposed HLHD system is based on the idea that composting machines can be transported between designated hubs and participating composting plants, where they carry out their specific activities during the composting process.

This novel approach has the potential to address the resource constraints faced by composting plants, improve efficiency, and enhance the overall quality of compost production.

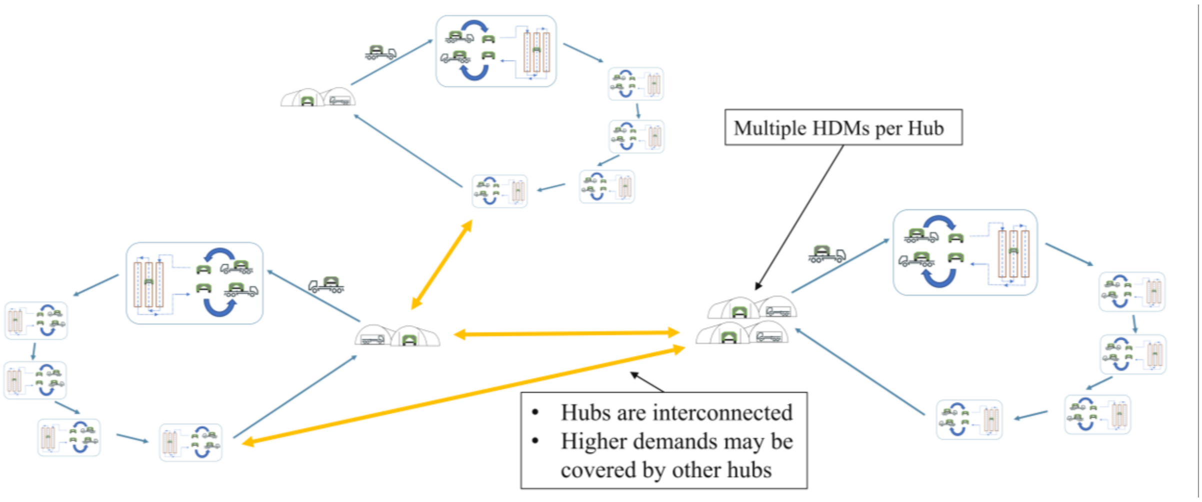


Figure 2: Overview of the Hyperconnected Logistic platform for Heavy-Duty machinery (HLHD)

Figure 2 shows the basic principle of the HLHD. This system starts at specific nodes (PI-Hubs) where the machines required for compost production are loaded onto trucks. The machines are then transported to the designated composting facilities, where they perform the required tasks. The HLHD platform operates within defined boundary conditions that are set in advance. One of the crucial requirements is the adherence to a self-defined time period for round trips. The specified time period is thereby set at one working day.

Following the Physical Internet concept, additional framework conditions must be established to augment the HLHD. One of the key considerations is the interconnectivity of individual hubs to ensure that high demand, including peak loads, can be accommodated by alternate hubs. Furthermore, the HLHD system envisages the potential for multiple machines to depart from each hub, if required. To maintain the scope of this publication, we will limit our analysis to three distinct scenarios, which will be subjected to a simulation-based study to evaluate their efficacy. Through this approach, we aim to provide a comprehensive understanding of the system's performance under varied conditions and identify potential areas for improvement.

2.1 Methods and Tools - Scenario 1: Small and medium-sized plants participate

The first scenario considers the participation of small and medium-sized composting facilities in the HLHD. This approach aims to provide an accessible and cost-effective solution for smaller composting facilities that may not have the financial means to purchase the necessary machinery to compete effectively in the market. To obtain data for the experimental investigation, surveys were conducted among composting companies in the central European region, which serves as a representative case study for the analysis. The surveys aimed to determine the duration for which composting plants utilize their composting machines on a daily basis. This information was subsequently utilized to develop profiles of typical composting plant sizes, which could then be applied to the scenario analyses. Percentiles were used to classify the composting plants according to their size and performance. The resulting profiles included a category of *small* facilities representing the 0th to 20th percentile, a category of *medium-sized* facilities covering the 20th to 80th percentile, and a category of *big* facilities covering the 80th to 100th percentile. This classification is used in the following scenarios to determine the number of composting facilities for each type. The analysis revealed that the region under consideration has a very communal situation, with many villages in rural areas having nearby composting plants, which tend to be small and medium-sized. As expected, larger composting companies were primarily located near urban centers.

The *PI-Hubs Location Planning* step is an important part of the HLHD model, where the most suitable locations for the PI hubs are determined. To accomplish this, a capacitated facility location problem is utilized, where the capacity of each hub is set to the number of composting facilities it is expected to serve. This method enables the identification of optimal hub locations that can provide the required services effectively. For a more detailed understanding of this approach, readers are encouraged to refer to relevant literature in the field. [18, p. 53]

The *PI-based network development* of the HLHD assumes that the composting machines are transported in a round trip manner from the PI hubs to the respective composting plants, and then returning to the initial location. However, it is important to note that this condition may be subject to change in future analyses, as the HLHD is a dynamic system that can be optimized and adapted based on new data and evolving requirements. In addition to the standard vehicle routing problem, PI-based network development for the HLHD includes two additional constraints, namely "multiple depots" and "time windows". Consequently, the optimization problem becomes a multi-depot heterogeneous vehicle routing problem with time windows (MDHVRPTW). Several studies in the literature have explored the MDHVRPTW, and readers interested in a more detailed explanation of this problem may refer to these studies. [19]–[21] As previously stated, the PI-based network development is governed by a constraint that requires the roundtrips to be completed within a predetermined time frame of 10 hours, corresponding to a typical workday duration.

2.2 Methods and Tools - Scenario 2: Small, medium and big plants participate to equal extent

The second scenario assumes that all composting facilities participate in the HLHD to an equal extent. The aim of this scenario is to investigate the feasibility and performance of the HLHD model when all heavy-duty machinery required for composting is shared among composting plants of all sizes. To be more specific, this scenario examines the effect of incorporating small, medium and big composting plants in the HLHD. It is worth noting that the duration of machine usage varies across different plant sizes, with larger plants requiring the machinery for a longer period compared to smaller plants. As such, this factor is taken into consideration in the scenario to ensure that the shared machinery meets the requirements of all participating composting plants.

In Scenario 2, the methodology used to obtain results is similar to the one used in Scenario 1. The first step involves the *PI-Hubs Location Planning*, which identifies the optimal positions of the PI hubs. The process is conducted by applying a capacitated facility location problem and taking into account the number of composting facilities to be visited. After the determination of the optimal positions, the next step involves the *PI-based network development*, which calculates the round trips starting from the PI hubs. As in the previous scenario, this step is a vehicle routing problem, considering the "multiple depots" and "time windows" constraints.

2.3 Scenario 3: Big plants participate part-time

The third scenario focuses on the assumption that small and medium-sized composting companies require the use of heavy-duty machinery and, therefore, participate in the HDLH. Meanwhile, the larger plants are considered to already own the necessary equipment and, as a result, do not require their participation in the HDLH. Nevertheless, the utilization of these large plants' machines is generally low, primarily because they are typically to be used mainly in the morning. This subsequently leaves the equipment unused in the afternoons.

As stated in the introduction, a key principle of the Physical Internet (PI) concept is to enhance the utilization of underutilized resources. As the heavy-duty machines owned by large composting companies remain idle during the afternoon, this underutilized resource can be made use of in accordance with the PI vision. In Scenario 3, it is assumed that these large companies will function as PI hubs during this particular time period.

The methodological approach for scenario 3 is similar to the previous scenarios. However, the key difference lies within the *PI-Hubs Location Planning*, since the precise location of the hubs is predetermined, as these are precisely the coordinates of the large composting plants. However, this assumption might require an extension, since the situation may arise that the number of the predetermined hubs is insufficient. This specific issue will be analyzed in greater depth in the corresponding results section.

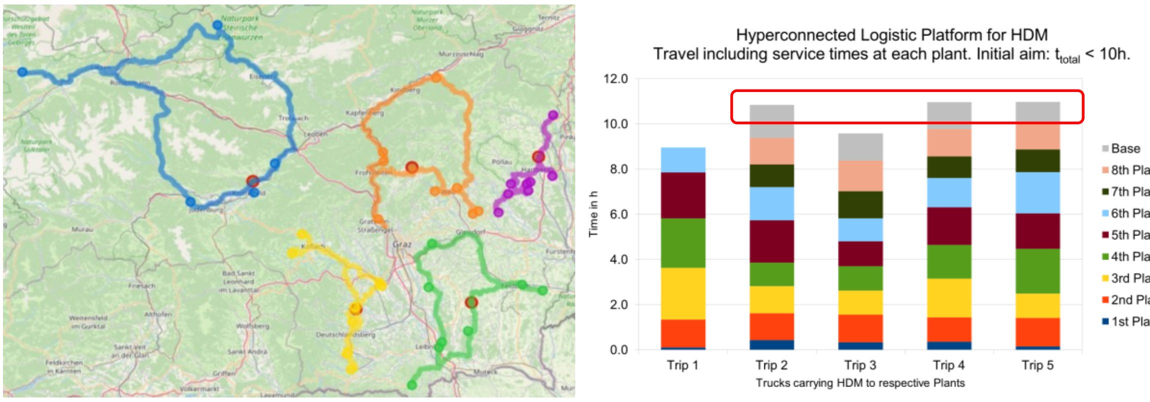
The *PI-based network development* for scenario 3 is similar to the previous scenarios. However, the time constraint of one working day has been adapted, and the routes must be completed within a shorter period of one afternoon, which is equivalent to 5 hours.

3 Results of the Simulation-Based Scenario Investigation

This section presents the findings of the simulation-based scenario analysis, which is organized in a similar structure to the preceding sections. Scenario 1 involves small and medium-sized facilities, Scenario 2 comprises all composting facilities, and Scenario 3 investigates the participation of small and medium-sized plants, with large composting plants functioning as hubs during the afternoon hours.

3.1 Scenario 1: Small and medium-sized plants participate

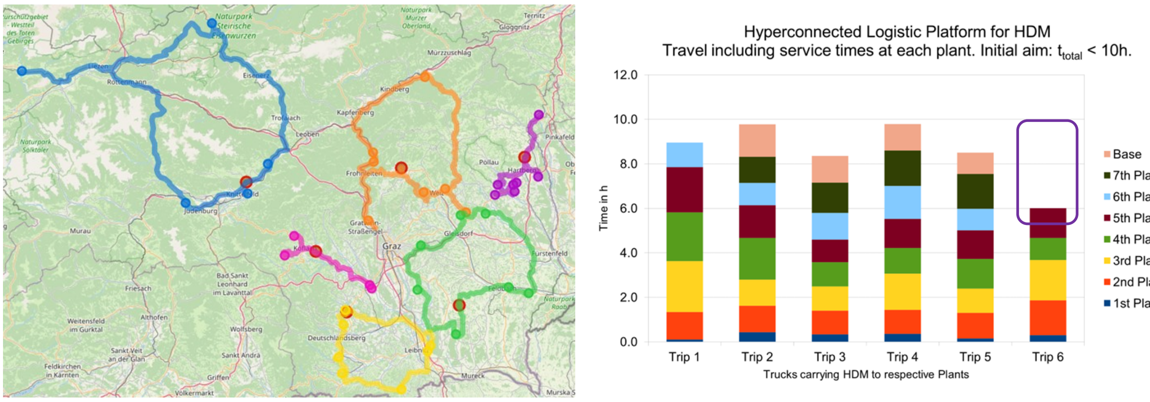
The results from the first scenario are shown in Figure 3. As can be seen, a number of 5 hubs was determined in the PI-Hubs Location Planning step. Based on these findings, 5 round trips were determined in the PI-based network development step, whereby the optimization condition was selected in such a way that the duration of all round trips is minimized. The calculated round trips are shown in Figure 3a, and the corresponding statistical evaluation is shown in Figure 3b. It is noteworthy that both the roundtrips and statistical analysis consider the time windows, which refer to the duration required by the heavy-duty machines at the composting site. The time windows are determined based on the profiles previously defined for composting plants.



(a): PI-based network development - Routes *(b): PI-based network development - Details*

Figure 3: Scenario - Initial results.

The results depicted in Figure 3b indicate that the initial requirement for the HLHD to cover all composting plants within a working day was not met, as roundtrips 2, 4, and 5 surpassed the given timeframe. To overcome this, an iterative approach was employed by repeating the PI-Hubs Location Planning and PI-based network development steps. In this process, a new constraint was introduced, whereby a maximum of 7 plants could be visited per hub.



(a): PI-based network development - Routes *(b): PI-based network development - Details*

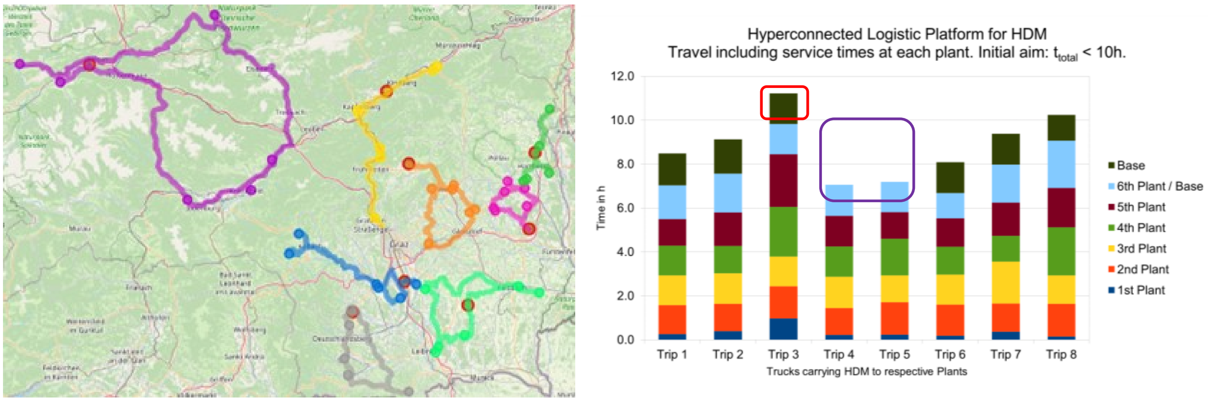
Figure 4: Scenario 1 - Refined results

The enhanced outcome is illustrated in Figure 4, depicting that 6 hubs were identified in the PI-Hubs Location Planning process. This outcome was then used to regenerate the roundtrips in the PI-based network development process, as shown in Figure 4a. It is evident from the statistical analysis presented in Figure 4b that by introducing an additional hub, the load on the other hubs was mitigated. Consequently, the initially set condition that the HLHD would serve all composting facilities within 10 hours was achieved. However, the suboptimal usage of hub 6 is the only trade-off. This particular aspect will be further addressed in the discussion section.

3.2 Scenario 2: Small, medium and big plants participate to equal extent

Scenario 2 is an extension of the former, and now also considers large composting plants. After incorporating the profiles for large plants that were defined previously, the mean duration of heavy-duty machinery usage on composting plants also increased accordingly. Subsequently, the optimal placement of the hubs was determined through PI-Hubs Location Planning, and the resulting roundtrips were computed using PI-based network development, as illustrated in Figure 5a. The evaluation of the individual roundtrips is depicted in the bar chart in Figure 5b.

Due to the inclusion of large composting plants, the number of hubs required increased to eight. In addition, a constraint is imposed that only a maximum of six composting plants per hub can be visited during a single roundtrip. The compliance with this constraint can be observed in Figure 5b, which indicates that the initial objective of completing the task in less than 10 hours is met for six out of the seven roundtrips.



(a): PI-based network development - Routes

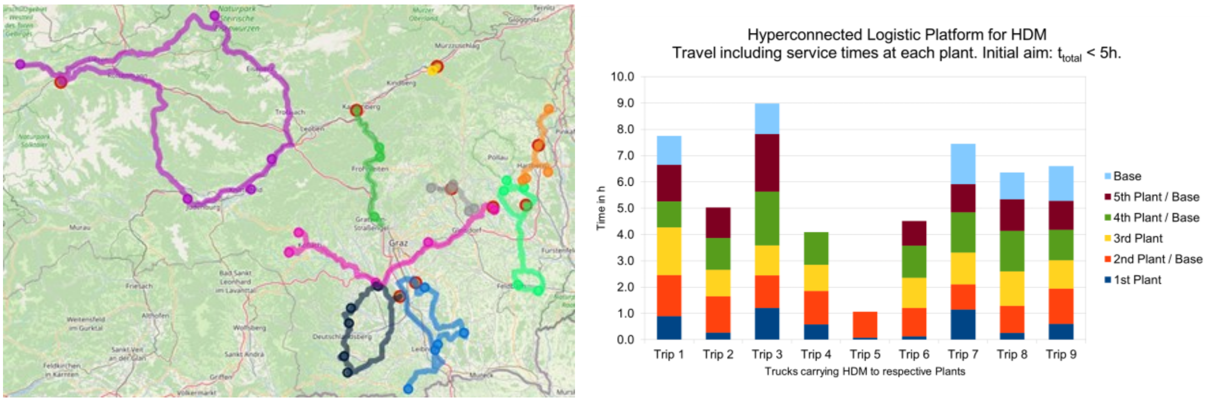
(b): PI-based network development - Details

Figure 5: Scenario 2 - Results

However, it is also evident that Trip 3 clearly exceeds this threshold. Despite this overshoot, it does not seem wise to increase the number of hubs. This becomes clear when we look at trips 4 and 5, as it is clear that these two trips have a low utilization rate. An increase in the number of hubs would bring Trip 3 within the limits, but would also reduce the overall utilization. It therefore appears reasonable to introduce local constraints to limit the duration of the individual round trips. Since the introduction of a local constraint inevitably leads to a reduction of the global optimum, this issue will be addressed in more detail in the discussion section.

3.3 Scenario 3: Big plants participate part-time

The third and last scenario assumes that the large composting plants participate in the HLHD by serving as hubs in the afternoon. The PI hub location planning step, which was performed in previous scenarios, was not necessary in this scenario because the locations of the hubs were predetermined by the locations of the large composting plants. The results of this scenario are presented in Figure 6, where the optimal number of hubs was determined to be 9 based on the predefined profiles for composting plants. The corresponding roundtrips generated by the PI-based network development are illustrated in Figure 6a. In this scenario, the constraint was set that only a maximum of 5 composting plants should be visited within one single round-trip, as depicted in the bar chart in Figure 6b. In contrast to the previous scenarios, the constrained applies that the HLHD must be carried out when the machinery is idle at the big plants, that is, in the afternoon. Therefore, the HLHD must be carried out within 5 hours. Despite having an increased number of 9 hubs compared to the previous scenarios, the time limit of 5 hours could not be achieved, as shown in Figure 6b. The reasons for this non-compliance with the given assumption are explained in the following.



(a): PI-based network development - Routes

(b): PI-based network development - Details

Figure 6: Scenario 3 - Results

On the one hand, it is clear that the positions of the hubs were predefined and therefore could not be optimally positioned by PI-Hub Location Planning. Secondly, it could be argued that the maximum number of composting plants to be visited per round trip was too high. On closer examination, however, it is immediately apparent that a reduction to 4 instead of 5 facilities per round trip inevitably leads to a situation where not all composting facilities can be visited. Since the exclusion of individual facilities from the HLDH contradicts the fundamental concept of the HLHD, this path is not pursued any further. Thus, it appears that the exclusive consideration of large composting plants as hubs is not sufficient and a further assessment is necessary. This will be addressed in more detail in the discussion chapter.

4 Discussion

In this study, several scenarios were explored to analyze use cases of the HLHD in the composting sector. Concerning Scenario 1, it was discovered that the initial results yielded a low utilization time, therefore further investigation was carried out. From a mathematical point of view, it is obvious that the introduction of local constraints leads in most cases to a reduction of the global optimal solution. In the context of the present use case, this implies that although the overall trip duration is increased, individual trips were able to comply with the specified time limit of 10 hours. Further, our findings suggest that an extension of Scenario 3 would be beneficial. Specifically, a PI-hub location planning with both fixed positions (existing composting plants) and variable positions would be necessary. The optimization algorithm should take the fixed locations in any case and calculate which variable locations must be constructed as hubs so that the HLHD works within one working day.

5 Conclusion and Outlook

In conclusion, the implementation of a Physical Internet based Hyperconnected Logistic platform for Heavy-duty Machinery (HLHD) has the potential to improve the composting industry's efficiency and overall quality. The proposed system aims to address the resource constraints faced by composting plants, which are often unable to acquire and operate essential machinery to compete with the ever-increasing composting rate and quality standards. The HLHD model is designed to transport composting machines between designated hubs and participating composting plants, where they carry out their specific activities during the composting process. The HLHD operates within defined boundary conditions, with adherence to a self-defined time period for round trips being a crucial requirement. This novel approach is a dynamic system that can be optimized and adapted based on new data and evolving requirements. Future research topics include, in addition to addressing the aforementioned limitations of the scenarios, an even more detailed view of the overall system. On the one hand, this includes an even deeper technical consideration of the optimization models, which also take dynamic conditions such as weather into account. In particular, severe weather events such as snow storms, which often occur in Central Europe during the winter months, are a major challenge for the logistics industry. Taking these factors into account in the HLHD would be essential. On the other hand, there was demand from the industry to make the HLHD even more adapted to customer needs. This includes a more dynamic customization of the routes based on customer requirements, including options for weekly scheduling of trips. The aforementioned topics are currently the subject of intensive research and will be published in due course.

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