Duck Box: Sensor-Based Material Flow Optimization for Economically and Energy-Efficient Intralogistics

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Abstract: Small batch sizes, increasing variant diversity and short delivery times raise the complexity of intralogistics in manufacturing companies. As a result, these challenges lead to economically- and energy-inefficient material flows. To address this issue, companies conduct material flow optimization. The decisive factor is that the planning often cannot be data driven. This is because there is no or insufficient data on internal material flows and optimization potentials cannot be fully exploited. The aim of this paper is to create economically- and energy-efficient material flows in manufacturing companies. The focus is on the development of a sensor prototype for the localization and utilization measurement of forklifts to close the current data gaps. Based on the current state of the art, the sensor prototype Duck Box is developed. This Indoor Positioning System (IPS) uses LoRa to determine the position of forklifts and an ultrasonic sensor to identify the utilization. The recorded and in real time analysed data is transmitted to a database via Long Range Wide Area Network (LoRaWAN). Finally, the developed prototype is applied and evaluated in a case study. The results of this sensor-based approach show the significant added value for the economically- and energy-efficient optimization of material flows.

1 INTRODUCTION

Manufacturing companies are continuously faced with new challenges. These include small batch sizes, increasing diversity of variants and short delivery times. To meet these, companies in most cases react by building up additional transport and personnel capacities. Since most internal transports are carried out manually, this increases internal logistics costs and reduces the company's success (ten Hompel and Kerner, 2015; Zajac and Rozic, 2022).

In recent years, manufacturing companies have therefore invested heavily in optimizing the internal material flow by eliminating weaknesses such as long transport distances, high shares of empty runs and low utilization of forklifts (Martin, 2016).

To address these issues, data is obtained and analysed, weaknesses are identified and optimization potentials are developed in the course of material flow planning (VDI 2498, 2011). This approach is shown in the following references.

Radhwan et al. (2019) conduct systematic, graph-based layout planning to increase material flow efficiency by up to 20 percent. A method for optimizing material provision is presented in Herbert et al. (2021). Krajcovic et al. (2019) develop a genetic algorithm to optimize material flows through layout planning. Belic et al. (2018) reduce internal material flow costs by optimizing layout, lead times and employee utilization. Chayaphum et al. (2019) determine the optimal number of forklifts in warehouse processes by using a simulation model.

In addition to the efficiency improvements required, the importance of sustainability goals as well as energy efficiency is rising (Ene et al., 2016, Zajac and Rozic, 2022). Intralogistics accounts with about 11 percent for a significant share of the logistics industry's greenhouse gas emissions, which in turn accounts for about 13 percent of total global greenhouse gas emissions. Since the forklift is an essential element of intralogistics, the scientific community has increasingly focused on the topic of

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sustainable and energy-efficient use of forklifts (Khoei et al., 2022).

Zajac and Rozic (2022) find that transport parameters such as transport speed or curve radius are directly related to forklift energy consumption and derives a calculation method for quantification. Pashkevich et al. (2019) and Ziólkowski et at. (2022) show that the utilization rate and transport distances significantly affect energy-efficient forklift use. According to the analyses of Fuc et al. (2016), for electric-powered forklifts, empty trips cause only up to 5 percent less energy consumption compared to trips loaded with one ton; diesel- and gas-powered forklifts show larger deviations. Ene et al. (2016) and Burinskiene et al. (2018) show that route optimization algorithms can reduce energy demand in warehouses and increase value creation.

One of the biggest challenges in material flow optimization is that planning often cannot be data-driven. This is because no or only insufficient data regarding the current material flows are available (Martin, 2016; VDI 2689, 2019). This inadequate data basis can significantly limit the level of detail, validity and objectivity of the methods presented and their results (Schwab et al., 2016). Efficient collection of actual, real-world data regarding utilization and transport distances travelled is an additional challenge (Li et al., 2021). Approaches to create the required data basis are offered by sensor solutions (Pashkevich et al., 2019) and Indoor Positioning Systems (Pascher et al., 2019).

The aim of this paper is to create energy- and economically-efficient material flows in manufacturing companies. The focus is on the development of a sensor prototype for the localization and utilization measurement of forklifts to close the current data gaps in the planning of internal material flows.

To achieve this objective, the following structure is chosen for this paper. Section 2 explains the state of the art of indoor positioning systems in intralogistics. Based on this, LPWAN and specifically LoRaWAN will be presented as an Internet of Things (IoT) technology suitable for logistics applications. These fundamentals serve as the basis for the development of the sensor prototype in section 3. The concept and its components are described in detail. In section 4, the resulting prototype is applied and evaluated in a case study in the building materials industry. Finally, the results are summarised in the conclusion and an outlook on further research is given.

2 RELATED WORKS

2.1 Indoor Positioning Systems (IPS)

IPS are defined as a wireless network of intercommunicating systems that are used to determine the position of objects or people in indoor areas. These systems consist of three main components: the location technology, the location method, and algorithms for data evaluation (Pascacio et al., 2019; Kaluža et al., 2017).

Compared to outdoor applications, indoor applications show high complexity. This is because the industrial environment has a significant influence on the reliability and robustness of measurement results. Furthermore, accuracy and range requirements differ significantly depending on the use case. For each specific use case, a suitable location technology (infrastructure-less or infrastructure-based), an appropriate location method (e. g. Time of Arrival - ToA, Received Signal Strength Indicator - RSSI) and target-oriented evaluation algorithms (e. g. triangulation) must be selected based on the prevailing requirements and restrictions (Pascher et al., 2019; Pascacio et al., 2021, Zheng et al., 2010). Therefore, many different indoor positioning systems in intralogistics appear in literature (Kaluža et al., 2017).

Chai et al. (2017) and Wang et al. (2014) use active radio-frequency identification (RFID) with reference tags to locate vehicles in warehouses. Motroni et al. (2021) developed a stationary RFID gate solution to identify forklifts and their direction of travel.

Burinskiene (2015) implements a combination of active RFID to locate forklifts and passive RFID to identify the material on the fork. Mel et al. (2016) and Müller et al. (2018) focus exclusively on tracking materials using passive RFID.

Barral et al. (2019), Halawa et al. (2020), Pilati et al. (2021), Frankó et al. (2020) and Gladysz et al. (2017), on the other hand, use Ultra-Wide Band (UWB) to collect intralogistic key figures from transport systems. Zhao et al. (2020) link UWB technology for locating forklifts with passive RFID for identifying materials and loading conditions.

Jung (2018) and Borstell (2016) are developing camera-based tracking systems for forklifts using reference markers. Li et al. (2021) use machine vision to measure utilization rates of forklifts. Kanakaraja et al. (2021) and Bencak et al. (2022) use Bluetooth Low Energy (BLE) to locate intralogistics objects.

The essential characteristics of all these applications are that, in addition to meet the intended use to 100 per cent, they should be realised cost-effectively and with little implementation effort. The ongoing technological progress of digitalisation strengthens the trend of IPS deployment in intralogistics (Pascher et al., 2019; Zheng et al, 2010; Ficco et al., 2013).

2.2 LPWAN and LoRaWAN

A radio-based technology that has rarely been used for localization in intralogistics is the Low Power Wide Area Network (LPWAN). This IoT technology is particularly suitable for sensors and applications with low data volumes and low transmission frequencies. Furthermore, LPWAN is characterized by the ability to be used in different environmental conditions as well as for data transfer over long distances with low energy consumption (LoRa Alliance, 2015; Pieper et al., 2019).
As Herion et al. (2020) state, LoRaWAN, a standard of LPWAN, shows itself to be a particularly suitable technology for the use in intralogistic warehouse processes due to these characteristics. First LoRaWAN demonstrators and pilot applications in the logistics context have been developed, as Kanakaraja et al. (2021), Pieper et al. (2019) and Fottner et al. (2021) have shown.

LoRaWAN serves as a communication protocol and system architecture. This standard uses LoRa as a wireless modulation that enables long-range communication links in the free regional ISM or SRD frequency bands (e. g. in Europe at 867-869 MHz).

As shown in Figure 1, LoRaWAN networks are star shaped (LoRa Alliance, 2015). They consist of the following components:

- End Nodes are bidirectional, asynchronous IoT devices that send data when it is available.
- Gateways receive the end node data and forward it to the network server via 3G, WiFi or Ethernet interface.
- The network server contains the data aggregation and processing.
- Application servers are defined as the end applications such as databases or web applications (Herion et al., 2020).

A special feature of this technology is that the end nodes are not assigned to a single gateway. Therefore, transmitted data is usually forwarded several times to the cloud-based network server, which then analyses and filters it. The advantage is that mobile end-devices do not have to be registered with new gateways and are therefore network-independent. A disadvantage of LoRaWAN is the low available data rate, which in turn has the advantage of low energy consumption (Herion et al, 2020; Pieper et al, 2019; LoRa Alliance, 2015).

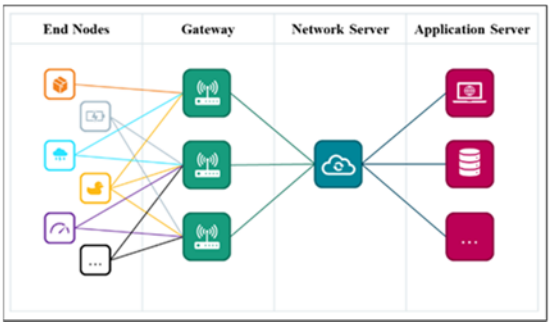

Figure 1: Design of LoRaWAN networks based on LoRa Alliance (2015).

3 SENSOR-BASED MATERIAL FLOW OPTIMIZATION

In the continuation of this paper, the described theoretical fundamentals are used to develop a LoRaWAN-based sensor prototype, called Duck Box, for the localization of internal transport systems, in this case forklifts. The aim is to develop a temporary real-time IPS that creates a location-based database that allows holistic material flow optimization. For this purpose, the concrete requirements are defined by the project team as well as by means of expert interviews, which are used for the design of the prototype:

- The IPS should be able to locate the transport flows of forklifts between sources and sinks.
- In addition, it should be possible to differentiate between empty and loaded runs to be able to calculate utilization levels.
- Furthermore, process and handling times during material pick-up and drop-off are to be identified.
- The sensor has to be flexibly usable on a wide range of forklift types and models.
- The components of the IPS should have an independent energy supply and be able to be used for at least 3 weeks without charging batteries.
- The system should be able to be set up and removed in a short time and no intervention in the IT infrastructure of the companies should be necessary.

- Furthermore, the implementation of the system should not cause any restrictions in the ongoing production and logistics processes.
- The generated data should be evaluated locally and in real time by the sensor and then transferred to an SQL database.

3.1 Tracking System

Based on the defined requirements, the conception of the IPS is started. Due to its optimal characteristics for mobile logistics applications, the LoRaWAN standard with its LoRa communication technology is selected as the location technology. Since LoRaWAN also transmits the Received Signal Strength Indicators, the RSSI method is defined as the location method. The algorithms for data evaluation are calculated locally by the microprocessor of the sensor, as defined in the requirements.

Based on these definitions, an IPS is developed that consists of three components:

- The repeater is used to define the sources and sinks of the material flows. For this purpose, it is mounted at the transfer points by means of cable ties or magnets. This component transmits a unique ID via LoRa, which is subsequently used for localization.
- The Duck Box is the mobile component of the tracking system. It is mounted on the front of the forklift using industrial magnets. The information sent by the repeater is received and evaluated by the Duck Box. By developing various algorithms, the material flow relation between the source and the sink of the transport as well as the dwell time at the source are calculated. Furthermore, based on these algorithms, it is possible to distinguish whether material handling is carried out at the source or whether the forklift has only passed the source. After calculating these key figures, the data is transmitted to the gateway via LoRaWAN standard.
- The gateway receives the data from the Duck Box and forwards it via 3G to the network server. A workflow is set up on this server, which saves the generated data in a SQL database.

Figure 2 shows the cooperation of the individual components in the LoRaWAN network. The grey arrows show the data transfer between repeater, Duck Box and gateway. It is important to add that both the reception ranges of the Duck Box and the transmission strength of the repeater can be individually adjusted according to requirements. This is shown in Figure 2 by means of the blue ellipses. This prevents several receiving areas from overlapping.

3.2 Loading Status and Degree of Utilization

For identifying the loading status of the forklift, the ultrasonic technology is used. Ultrasonic sensors emit ultrasonic signals at regular intervals, which in turn are reflected by objects on the fork of the truck. The reflected ultrasonic signals are received by the sensor. Based on the time difference between sending and receiving the ultrasonic signal and multiplying it by the speed of sound, it is possible to determine the distance between the object and the ultrasonic sensor. If this distance is greater than the length of the fork, the forklift is travelling empty, otherwise it is travelling under load. Based on the identification of the empty and loaded runs and in combination with the location concept, this enables analyses of the utilization levels per transport relation. The source, the sink, the dwell time at the source, the transport route incl. intermediate stops and the loading status of the transport relation thus form the data set.

The effect of the direct assignment of the loading status to the transport relation is also used to minimize the data volume to be transmitted and to comply with the restrictions of the LoRaWAN standard. Therefore, the change of the loading state at a repeater serves as event, which triggers the data transmission via LoRaWAN. This functional principle can be seen in Figure 2. The forklift equipped with a Duck Box (D) starts its unloaded transport at source R1. Arriving at the reception area of the sink R2, the forklift picks up material. The loading status changes to loaded. This event then triggers the data transmission to the gateway (G).

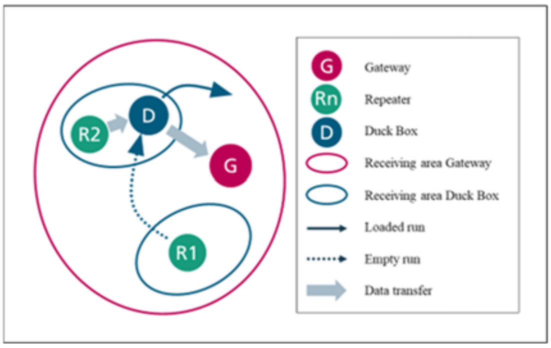

Figure 2: Tracking system Duck Box.

3.3 The Developed Prototype: Duck Box

For the implementation of the concepts, suitable hardware modules were selected, programmed, designed and developed:

- An Arduino-based microcontroller is used to locally evaluate the measured data of the positioning and the loading by means of the developed algorithms.
- A Murata LoRa chip, which operates at a frequency of 868 MHz, is directly connected to the microcontroller, and is used for the positioning system as well as for real-time data transmission. This component is supplemented by a dipole antenna to achieve greater ranges.
- In addition, the commercially available ultrasonic sensor US100 is connected to the microcontroller to measure the utilization of the forklift.
- Since these modules require a nominal voltage of 3.3 volts, suitable protected Li-Ion batteries were selected for this purpose. With a capacity of 13,800 mAh, the required runtime of about three weeks can be guaranteed.
- To protect the sensor modules and the power supply from the harsh operating conditions in industrial environments, a robust housing consisting of two halves was designed and produced by means of additive manufacturing. A CAD model of the developed solution is shown in Figure 3.
- Industrial magnets are screwed into the housing for easy mounting on the forklift. For this purpose, hexagon nuts are inserted into the housing. This screw connection also serves to close the two halves of the housing.

The repeater consists of the same modules as the Duck Box except the ultrasonic sensor. In addition to the existing freely available gateways, a RaspberryPi-based device equipped with a 3G SIM card is temporarily placed in the area of operation.

The data from the gateway is transmitted to the open-source network server The Things Network. To be able to store the generated data, an interface to a cloud-based SQL database was created by means of a webhook integration and an automated online workflow. The database contains the source-sink relationships, the dwell times and the loading states of the transport relations. This data is accessed using a Tableau dashboard to visualise the collected data appropriately. As part of the following case study, the individual functions of the dashboard will be shown.

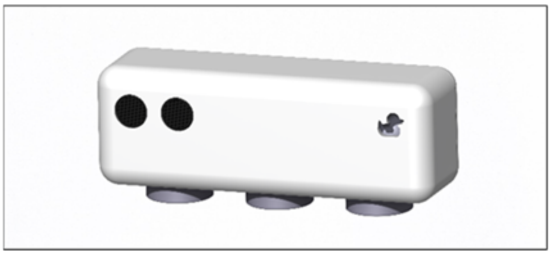

Figure 3: CAD model of the Duck Box.

4 CASE STUDY

4.1 Execution of the Case Study

The developed IPS was applied and evaluated during a case study at a company in the building materials industry. At the company's Austrian location, various building materials such as mortar, adhesives and sealants are produced, temporarily stored and loaded into trucks. Due to the growth in production and the associated growth in structures, transparency in intralogistics was increasingly lost.

Since there were no applicable postings in logistics, it was not possible to optimize the company's material flows to increase the efficiency and to achieve the sustainability goals in intralogistics such as socially evenly distributed personnel deployment or reduced energy demand.

For this reason, the developed prototype Duck Box was used over a period of three weeks to create the missing data basis. All five forklifts of the finished goods storage were equipped with a Duck Box. Fifteen material handling positions (sources and sinks) were equipped with repeaters. The gateway was used for data transmission.

The data evaluation was done using the developed Tableau dashboard, which is shown in figure 4. This dashboard consists of a layout in which the sources and sinks are drawn by means of circles. The larger the diameter of the circle, the longer the dwell time at this position during material handling. In addition, this figure is supplemented with a distance intensity diagram. The further the distances and the more frequently this transport relation is travelled, the more critical this transport relation is. The most frequent transport relations are displayed at the bottom of figure 4. The light blue bars represent the empty runs, the dark blue ones the loaded runs.

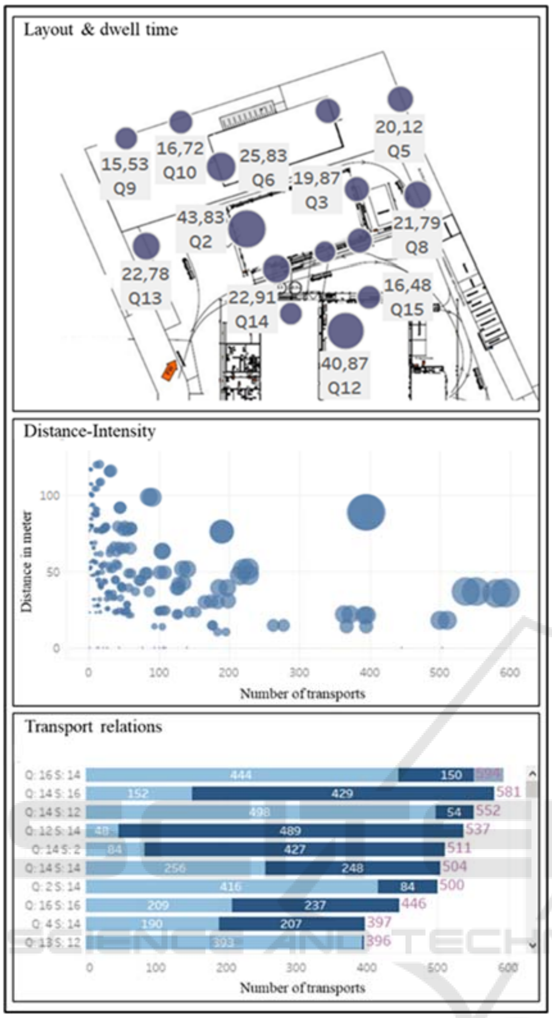

Figure 4: Visualization of the results.

Based on these results, the following optimization potentials were identified:

- The greatest transport intensity is caused by the storage of finished goods in storage area Q13. Due to the frequency of this transport in combination with the long transport distance, a concept was developed to minimize these efforts by reorganizing the finished goods storage areas. As a result, the entire warehouse layout at the site was revised. Q13 was placed closer to production to be able to reduce transport intensities. Sinks that were only used very rarely were placed at a greater distance from production.
- Furthermore, the utilization of all forklifts showed that very often paired transports occur, loaded in one direction and unloaded in the other. As solution, it is planned to increase the loading factor. Therefore, a forklift that performs storage operations should be equipped with long forks to be able to transport two pallets per transport.
- All forklifts are assigned to defined tasks. By comparing them, it was found that the transport tasks were very unevenly distributed due to this fixed assignment. This resulted in high workloads for some forklift drivers. A concept has been developed for more even workloads for forklift drivers, for example by no longer loading trucks and swap bodies separately.
- Finally, it was found that at source Q12, the pick-up of finished goods, the dwell times were twice as high compared to the other material handling positions. By rearranging and adapting the racks used there, handling activities could be significantly reduced. In particular, the short forward and reverse setting of the forklifts was improved. This has made a key contribution to increasing energy efficiency in this area.

By implementing the specified measures, the following optimizations could be calculated for this specific case study:

- Transport intensities could be reduced by up to 25 percent.
- The utilization rates of the forklifts were improved by at least 18 percent.
- The energy efficiency of material transport in the finished goods area was improved by up to 20 percent.

4.2 Validation of the Prototype

Regarding the Duck Box IPS, it can be concluded that during the case study all components of the tracking system operated stably and without interruption over a period of three weeks. The data transmission via LoRaWAN also worked without any problems. No intervention in the company IT network was necessary. The implementation effort was limited to about one day. Although the Duck Box was mounted on different forklift models, there was no impact on the company's operational processes. The evaluation within the case study shows that all defined requirements are fulfilled by the Duck Box.

Compared to state-of-the-art IPS, the setup within a day and without interfering the operations in warehouse has shown to have significant potential. For example, the use of the ultrasonic sensor made it possible to collect utilization rates without applying information carriers such as RFID tags to products. The use of LoRaWAN for positioning and data transmission significantly reduced the complexity of the IPS. In addition, the implementation of a separate IT network without interfering with the company's infrastructure was beneficial. These measures increase the usability of the IPS.

Since the developed IPS is designed for temporary analyses of up to three weeks, the Duck Box IPS shows disadvantages for permanent applications compared to state-of-the-art solutions, e. g. due to the need for regular battery charging. In future case studies the scalability of the developed system with increasing number of material handling positions and forklifts must be evaluated.

The state-of-the-art in conventional material flow planning shows different approaches to optimize material flows. These methods usually assume an optimal data basis. As Schwab et al. (2016) show, the lack of available data limits the results of these methods. The developed IPS demonstrates a sensor-based approach that achieves novel, data-driven results despite this lack of data, as shown in the course of the case study. Recorded, actual transports, utilization rates and dwell times have been used as the data basis, which are partly difficult to determine with conventional methods. In summary, the use of sensors shows a significant added value for the creation of holistic, valid and efficient material flow planning.

5 CONCLUSIONS

In this paper, a novel sensor prototype called Duck Box is developed. This LoRaWAN and ultrasonic-based IPS enables the implementation of sensor-based material flow optimization. The data generated in the process creates transparency in the intralogistics of manufacturing companies by recording the actual utilization, transport intensities and material flows as well as dwell times of forklifts without the need for posting data.

The evaluation of the prototype in a case study in the building materials industry has shown that the generated sensor data creates novel and holistic material flow optimizations. In particular, the actual utilization rates and determined transport intensities show a clear added value in planning and have led to optimization potentials of up to 25 percent in the specific case study. In conclusion, the sensor used and the data generated lead to the creation of more economical and energy-efficient material flows.

The next step is to develop a dynamic optimization algorithm based on the sensor data. This algorithm will calculate recommendations regarding the optimal utilization of forklifts, the ideal distribution of tasks and the most effective arrangement of sources and sinks in the layout. The evaluation of the results is to be standardized regarding economic and sustainability criteria.

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