University of Stuttgart
Germany

Institute of Architecture of Application Systems (IAAS)

Chair of Service Computing

University of Stuttgart
Universitätsstraße 38
D–70569 Stuttgart

Master Thesis

Analysis and Development of a Digital Picking System using IoT and Logistic 4.0

Aniruddha Prashant Jahagirdar

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Examiner:	Prof. Dr. Marco Aiello
Supervisor:	Mr. Roeth Christoph
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Abstract

Order picking is a crucial step in nearly all distribution networks and has a significant impact on how well warehouses run. Even though the majority of businesses still use manual order picking, development into diverse options for optimizing order picking operations or providing technological support for human order pickers is advancing quickly. A development in the logistics industry known as Logistics 4.0, or Industry 4.0 in logistics sector is taking place; it addresses new goals and the use of technology to handle impending issues in logistics and warehouse operations. More than half of a warehouse's operational expenses are largely linked to order picking, which is the process of collecting material from the warehouse and delivering it to the packing station. Order picking procedures still primarily rely on manual labour, which notably contributes to the relatively high process costs, despite the prospect of digitising these procedures growing.

In this study, a new way is proposed to optimise the manual operations of the paper-based order picking system by integrating the warehouse routing problem with an interactive webpage to give routes for pickers and order data in order to improve productivity and lower picking error rates. To evaluate the current level of knowledge in this area, a thorough literature study is conducted, and potential research areas in order picking are identified. Along with this, various Travelling Salesman Problem (TSP) heuristics are also examined, and thorough cost and performance analyses are done for various TSP heuristics. Additionally, an economic analysis is performed where several factors are taken into account for both the current paper-based system and the recently built digital system. In the end, this thesis work discovers that the digital picking method performs better in terms of worker ergonomics and efficiency than the traditional paper-based approach. Under the general conditions set, this is the only order picking solution that requires no modification of the warehouse's environment and a minimum of initial investment in infrastructure.

Keywords: Industry 4.0, Logistics 4.0, Warehouse Optimisation, Order Picking, Travelling Salesman Problem (TSP)

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1 Introduction

With a problem statement and research questions pertinent to the thesis study, this part gives an overview of the context and motivation for this thesis. Along with an outline for this thesis report, this part also contains a brief summary of the technique used in this study.

1.1 Context and Motivation

The Internet of Things is revolutionising the capabilities of internet-connected endpoints, and it is being driven by sensor networks, mobile devices, wireless communications, networking, and cloud technologies. There is a rising demand for highly customised products and services. The intricacy is increased by the company's extensive worldwide reach and varied product line. The size and complexity of today's retail floors make visibility a major challenge. Due of its increasing complexity, it is difficult to handle using conventional methods. For many businesses, logistics management is one of the most crucial tasks. The objective of logistics is to provide efficient material and information flows along the whole supply chain (logistics network), which consists of the physical and communication pathways connecting numerous, interrelated organisations from their points of origin to the final end customer. Technology advancements and a rise in globalisation have made logistics a more competitive industry for businesses. Fast and precise deliverers will have an advantage in the market. Fast delivery requirements have a significant influence on warehouse operations. As supply chains get shorter and more linked, business operations become more globally diversified, consumers become more demanding, and technological advancements advance quickly, warehouse challenges evolve over time and need new solutions. Companies are employing creative strategies, such Warehouse Management Systems (WMS), to satisfy these expectations WMS.

Order picking is a crucial step in almost all supply chains, and it significantly affects how efficiently a warehouse operates. The majority of organisations still utilise manual order picking, although research into ways to automate order picking tasks or use technology to support human order pickers is quickly expanding. A solution or a replacement to manual order picking is currently in the market with various different technologies like Pick to Light (PTL), pick to voice, Augmented Reality (AR), Automated Storage Retrieval Vehicles (ASRV), Radio Frequency Identification (RFID), etc. The advantages of warehouse automation include lower labour expenses, fewer mistakes, and increased productivity. As humans move forward with new technology to optimise warehouse operations, there are various new challenges with order picking process. On the one hand, regular orders from customers arrive late due to picking of products from a large warehouse. On the other side, order picking times must be shortened in order to give clients quick service. Researchers and plant managers in warehousing are always working to create and implement novel picking methods and picking procedures in warehouses in order to tackle these new problems.

In this thesis, a novel modelling and analysis method for order picking system performance is presented. In this thesis, specifically a digital tool is creted to calculate the effects of a digital picking system that replaces the current paper-based system. By studying a real-life scenario, the proposed system provides efficiency, achieve higher pick throughput and reduced errors. The method mentioned in this thesis offers deeper insights for warehouse operations and a realistic, affordable way to enhance the performance of the order picking system from both an academic and practical standpoint.

1.2 Problem Statement

The "digital picking system"concept emphasises cutting down on pickers' travel time while also making their work more comfortable. Additionally, it emphasises accelerating delivery with no to little mistake. The suggested solutions use äutomated technologies.Äccordingly, many systems attempt to concentrate on either total automation utilising ASRV or robots or partial automation with significant initial investment, such as pick to light, pick by voice system, or pick by vision. Here, however, there is an attempt for a more economical strategy by fusing an existing database with a fresh digital environment that can be used on any mobile PC. With this strategy, we are able to adapt the digital platform to the needs of the warehouse without having to make any infrastructure adjustments in a real warehouse. The following are a few broad questions regarding this thesis' application of the concept. (1) How can an existing process be seamlessly connected with a digital picking system without causing significant changes to the operation? (2) What potential further benefits may this digital picking method offer? (3) Are digital picking methods actually superior to the current paper-based ones? (4) What other advantages would the suggested approach have over a picking system that is entirely automated? (5) How do mobile digital devices differ from pick-by-voice and pick-by-vision systems?

1.3 Research Questions

In this section, mainly the concentrate is on the research components of the study and list the queries we used to determine the overarching goal of the work. The base for this thesis work is based upon the concept of TSP. One of the most important combinatorial optimization issues and one of the NP-hard problems is a Steiner Traveling Salesman Problem (STSP), a variant of the traditional Traveling Salesman Problem, is a classification for the problem of ordering and routing order pickers in conventional rectangular warehouse systems with multiple parallel aisles. Here are a few research topics that will help this thesis project become more motivated.

1. What efficiencies can be gained by adopting a digital picking system versus a manual one in terms of (jobs/day, euro/job, and throughput)?
2. Evaluate different TSP algorithms for the given warehouse scenario and compare its performance with cost and computation time
3. What are the advantages of these systems in terms of productivity, efficiency, profitability, and ergonomics?

4. What are the advantages of digital picking system over existing systems such as pick to light, pick by voice, and pick by vision?
5. Is the proposed system scalable and if so, then what are its limitation to scalability?

1.4 Methodology

Contributions are clear from the research questions that answer for thesis work. Methodology used for answering the proposed question in research question section are as follows:

1. Conduct literature survey to study current state of the art and best suitable technology to be used.
2. Develop a solution for the warehouse routing problem for the order pickers in the warehouse for support. The routing is done with routing algorithms.
3. Build a prototype that can fulfil the use cases of this thesis work using existing database with an additional database for visual aids.
4. Comparison of performance of different routing algorithms based on cost and computational time.
5. Comparison of developed prototype with existing paper-based system in terms of efficiency by preparing different test case scenarios and economically by conducting an economic analysis.

1.5 Organization of Thesis

This section describes the thesis organisation and gives an overview of each chapter presented in this thesis:

Chapter 2 describes the background of the Bauer Gear Motor GmbH and the motivation behind implementing the proposed solution in Esslingen warehouse.

Chapter 3 describes all the relevant information related to the regarding a range of ideas and expressions connected to this thesis and their functions in the current order selection process. The paper-based methods that are still widely used in many industries to handle warehouse and logistics operations are discussed in this chapter together with the new supply chain technologies known as Industry 4.0 and Logistics 4.0.The information on non-deterministic polynomial-time hardness (NP-hard) problems and TSP algorithms, which are used for warehouse routing, is provided in the chapter's conclusion.

Chapter 4 provides all the important research for this topic, including information on the methods used to improve the order-picking process at the warehouse and the effectiveness of the routing algorithms there. There has been discussion of a number of articles and their work that employ similar methods and have the same goal of improving warehouse order picking efficiency.

Chapter 5 provides an outline of the design strategy utilised to develop the suggested solution. Customers have practically perfect access to the digital paperless alternative for picking up their goods. The overall operation of the system and anticipated results are outlined. Additionally, a more thorough description of the TSP heuristics chosen for this thesis' assessment is provided.

Chapter 6 discusses the tools used in developing the proposed system and how data has been collected for conducting the analysis for this thesis work.

Chapter 7 offers a summary of the final prototype's results, which were built for the digital order picking system for the Esslingen warehouse of Bauer Gear Motor GmbH. In order to analyse the effectiveness of the TSP heuristics utilised and their impact on day-to-day operations in the warehouse, this chapter also covers data analysis and economic analysis

Chapter 8 is the thesis's last chapter, which discusses the thesis's conclusion with its limitations to current state of the art and its potential future directions

2 Overview and Motivation of Bauer Gear Motor GmbH

Since its founding in 1927, Bauer Gear Motor has expanded internationally to establish itself as a leading supplier of excellent geared motors. Engineers at Bauer provide technologically sophisticated solutions with energy-efficient motors and the best gearboxes to give clients the lowest total cost of ownership.[8]

There is one assembly facility for Bauer Gear Motor in Esslingen, Baden-Württemberg, Germany, and a warehouse there as well. Numerous gear motor types, including helical, bevel, worm, parallel shaft, etc., are assembled at Bauer Gear Motor's Esslingen facility. This facility exports the spare parts required for these gearboxes to sister companies and customers in nations like Egypt, Australia, Brazil, Canada, Chile, China, England, India, Israel, Japan, Columbia, Korea, Mexico, New Zealand, Norway, Philippines, Singapore, South Africa, and USA. In addition to assembling and shipping the finished product to customers, this facility also exports the spare parts needed for these gearboxes to these countries as well. With a steady increase of spare parts orders over the past years and an approximate growth of 25% over the next 5 years , an effective order picking system is required to help the pickers perform their daily tasks because there are so many clients in many nations to serve. Currently, a paper-based approach has been used to complete the order choosing procedure. The procedure includes printing the order each morning, categorising the products by country, picking up the parts, and finally packing. The picking procedure under the existing system is time-consuming, ineffective, and adds to Carbon dioxide (CO2) footprints due to all the paper that is discarded once the selecting process is complete. The Esslingen plant's spare parts departments are the primary target of the suggested digital solution in order to improve productivity and decrease picking mistakes, which would ultimately shorten customer wait times and remove any hidden costs associated with replacing the wrong sent item. The goal of this thesis is to present a path to the picker with the shortest possible trip distance together with precise locations, details, and an image of the component to be selected on a computer screen. In this thesis, multiple TSP heuristics have been built to test the performance of these heuristics based on cost and calculation time. These heuristics have been applied to various routing issues.

3 Background Information

This chapter informs us about a variety of concepts and terms associated with this thesis and their roles in the present order selection procedure. This chapter discusses the new supply chain technologies known as Industry 4.0 and Logistics 4.0, as well as the paper-based systems that are still widely employed in many sectors to manage warehouse and logistics operations. This section also discuss the warehouses, their layouts, and the order picking procedures that work well with the various types of layouts now in use. This chapter concludes with information on NP-hard issues and TSP algorithms, which are employed for warehouse routing.

3.1 Industry 4.0 and Logistics 4.0

3.1.1 Industry 4.0

Industry 4.0 mainly is the development and use of cutting-edge information and communication technologies. The major objective is to promote the intelligent networking of products and processes along the value chain in order to employ organisational processes more effectively in the production of goods and services that will benefit customers by providing them with unique goods and services. The fourth industrial revolution, which is now being referred to as a collection of connected changes in the industrial sector: 4.0 Industry. [3][9][5]

The invention of the steam engine and the introduction of powerful mechanical production tools marked the start of the first industrial revolution. The introduction of electricity, which made the assembly line and conveyor belt possible, defined the second industrial revolution. Through the widespread use of electronics and information and communication technologies, the third industrial revolution brought to the automation of manufacturing processes. The fourth industrial revolution, sometimes known as "Industry 4.0," emerged as a result of the development of cyber technologies and their integration into digital ecosystems across all industry value chains. At the 2011 Hannover Fair of Industrial Technologies, the term "Industry 4.0" was first used [5]. Since then, a lot of businesses have begun to create solutions that adhere to the idea of Industry 4.0. The development of such solutions is supported by several governments, including those in the United States, Europe (with a focus on Germany), and Japan. This confirms that the main industrial powers and actors consider the new industrial period as strategically important [6]. Industry 4.0's primary goal is, generally speaking, the emergence of digital manufacturing, also known as a "smart" factory, which entails smart networking, mobility, flexibility of industrial operations and their interoperability, and integration with clients and suppliers, and the adoption of novel business models [33]. The intelligent networks built on cyber-physical systems are what are known as the fourth industrial revolution's distinguishing characteristic. Physical and engineering systems that can be monitored, coordinated, controlled, and integrated by a computing and communication system are known as Cyber-Physical Systems (CPS). In a CPS, decisions are made using a core computing system and a network architecture that includes sensors and actuators that interact with the physical world. The widespread use of technological applications and the expansion of wireless embedded sensors and actuators are fostering the creation of a number of new applications in fields like manufacturing, logistics, transportation, health care, autonomous vehicles, and machine learning, as well as advancing the technology of already existing ones like Supervisory Control and Data Acquisition (SCADA) [10]. Figure 3.1 gives us a general idea of general architecture of cyber physical systems.

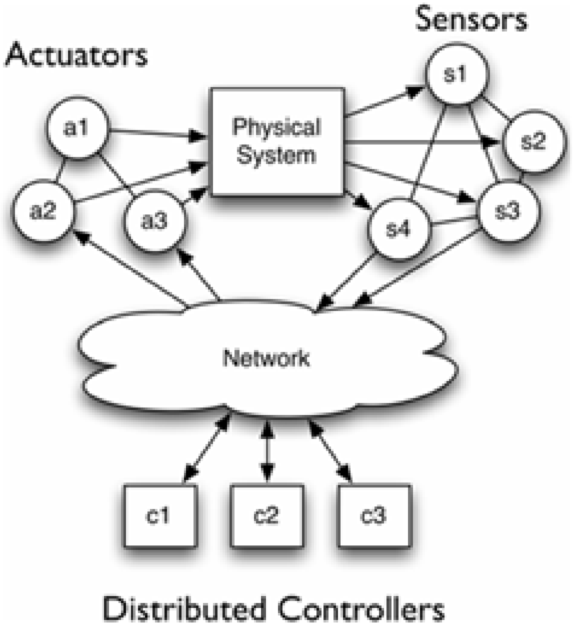


Figure 3.1: General architecture of cyber physical systems. [34]

The Internet of Things (IoT), often referred to as the Industrial Internet of Things (IIoT), has revolutionised manufacturing, service delivery, logistics, and resource planning in a way that is more effective, cost-efficient, and characterised by better and enhanced communication. Shorter production cycles, real-time customer demands integration, and order fulfilment, shipping, and dispatching are all benefits of technological development. Additionally, from the perspective of organisational structure, Industry 4.0 includes vertical integration of subsystems within the factory in order to create a flexible and adaptable manufacturing systems, horizontal integration of networks across the entire value chain to enable product customization, and through-engineering integration across the board. Two fundamental building blocks for engineering integration across processes are the horizontal integration of businesses and the vertical integration of production inside the plant. The figure 3.2 illustrates how technology and services are related in the Industry-4.0 production idea.

3.1.2 Logistics 4.0

The need for highly customised goods and services is always rising. Thus, logistics for both inbound and outgoing traffic must adjust to this dynamic environment. It is too complicated to be managed using standard planning and control procedures. [47]

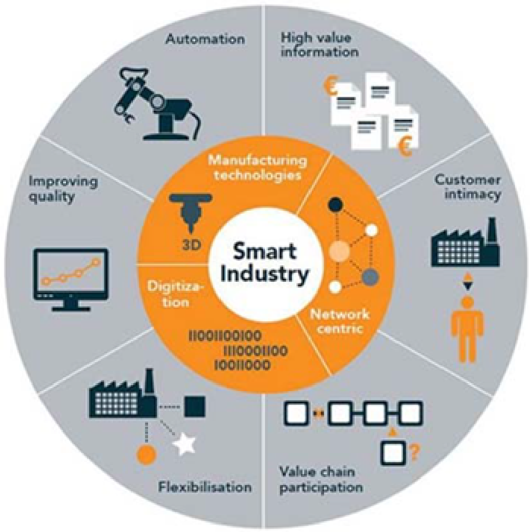


Figure 3.2: Industry 4.0 Concept. [16]

The utilisation of logistics in conjunction with the additions and advances made by CPS is referred to as “Logistics-4.0” in its terminology. The same requirements that apply to smart services and smart products in logistics also apply to logistics 4.0. Then, it must take into account that “Smart Logistics” can be defined using the same technology-driven approach as“Smart Products” and “Smart Services” [6]. The ones that can carry out duties that are typically handled by individuals are considered to be smart products and services. Additionally, they enable delegation so that workers may concentrate on jobs requiring greater intelligence than automatic procedures or the plain smartness that a smart product or smart service can offer. A logistics system called “Smart Logistic” can increase flexibility, allow for better adaptation to market changes, and bring a business closer to its clients’ demands. The level of customer service can be raised, manufacturing can be optimised, and storage and production costs may be reduced as a result. The logistics industry is evolving in accordance with Industry 4.0 and is designated as Logistics 4.0; it addresses new goals and the application of technology to handle these issues. According to its definition, logistics 4.0 is “the logistical system that supports this expansion in industry and commerce utilising digital technologies and enables the sustained meeting of individualised client expectations without an increase in prices” [60].

Since the economy became industrialised, global trade has evolved from being primarily utilised for the exchange of luxury goods to becoming commonplace in all economic sectors. The growing global division of labour and digitization have led to a major increase in the exchange of goods and data in recent years. It is crucial to have efficient logistical processes that adhere to the increasingly exact time requirements of the supply chain, are highly automated, and take climate change and environmental protection into account. Fig 3.3 shows us the importance of logistics industry.

In [4] the respondents believe logistics has a promising future. The majority of respondents to the study think that data silos will soon be obsolete and that the usage of Artificial Intelligence (AI) and paperless procedures in warehouse operations will increase dramatically. Similarly, two-thirds of respondents believe that businesses that share data will have longer-term success.

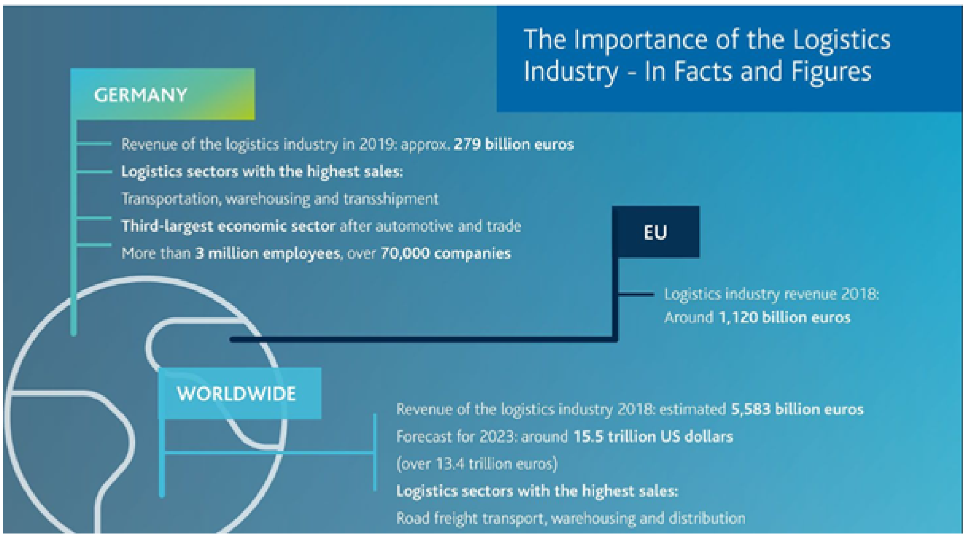


Figure 3.3: Importance of logistics industry. [4].

It can be argued that there is a lot of room for development in the logistics sector. Logistics professionals have already adapted to modern technologies, such as voice and gesture control. Systems like pick-by-voice or pick-by-light, for example, have been successful in order picking. Data glasses are used in combination with augmented and virtual reality to sort the components. Given the continuous growth of e-commerce and the aim to lower the cost of the last mile, autonomous cars are expected to replace delivery in the near future. Drones and autonomous delivery systems may potentially be involved in this.

3.2 Paperless Systems

Companies often utilised a paper-based approach to keep track of their warehouse operations before the introduction of digitalization. More businesses are beginning to transition to paperless warehouses as a result of technical advancements, environmental issues, and productivity gains. However, there are still a lot of companies that rely on paper processes and are hesitant to move away from them. Due to how established the conventional paper-based techniques were, businesses have a tendency to put off switching to a paperless warehouse. Many warehouses were built with paper-based record keeping as their only means of operation. The majority of items were kept on paper, including invoices, work schedules, bills of materials, routing, receipts, and material sheets. Therefore, for a traditionally run paper-based warehouse, the initial expense and effort of becoming paperless may seem a little overwhelming. Although most organisations are aware that eliminating paper will help warehouse operations, there are many more advantages that might not be immediately obvious. The main reasons in favour of abandoning paper-based warehousing practises and transitioning to digital ones are listed below.

- More precision - Paperless warehouses are more accurate warehouses. The paperless technique lowers mistakes since there are fewer reporting delays and exceptionally exact data input and record maintenance. The usage of a portable gadget will improve the accuracy of the warehouse

- Improved visibility - Finding every inventory item's location is no longer a challenging task that is prone to human mistake. The capacity to handle complexity in warehouse operations is enhanced by increased visibility.
- Increased productivity - Paper-based systems need a lot of labour and resources since it costs money and time to run printers, buy supplies, and handle tonnes of documentation. It takes time and is subject to prejudice and human monitoring to track productivity and performance using handwritten records. The time used to manage paper-based records might be used for higher-value tasks. A paperless system offers chances to save expenses and boost efficiency in almost every aspect of business operations by automating manual procedures.
- Cost and environmental effect reduction - The use of copious amounts of paper, ink, and printer may be expensive and has a bad effect on the environment. Moving to paperless systems and procedures would not only save operational expenses but also increase employee wellness, reduce carbon emissions, and better use available warehouse space.
- Enhancing client service – Digital systems' decreased errors rate improves customer service and frequently prevents the dispatch of the incorrect items in an order. This prevents delays at the customer's end and hidden costs associated with replacing the incorrect product with the correct one.

The possibility of better alternatives to the conventional way of paper-based warehouse management has been made possible by technology. It might be utilised throughout the whole logistical chain. Potential savings can be found in a variety of areas, from labour reduction to increased accuracy, better space usage, and higher performance. When paper-based operations are replaced with mobile devices and manual processes are replaced with automated processes, the aim of a paperless warehouse may be achieved. When a system is employed a warehouse management system that includes barcode scanning and real-time record management, paperless operations are achievable. Although there can be a temporary decrease in productivity as the company make the shift, going paperless will rapidly pay for itself in all the warehouse operations

3.3 Warehouse

"Warehouses form an important part of a firm's logistics system allowing storage or buffering of products at and between points of origin and points of consumption" [20]. Based on NACE Warehousing and Transport Support Services Statistics [55], in the European Union, there were over 1.2 million warehouse facilities as of 2019, employing over 10.448 million people, and making 1.4 billion euros in revenue. In the transportation and storage services industry of the EU in 2019, the apparent labour productivity was €48 800 per person employed, while the average personnel expenses were €35 200 per employee. [55]

The majority of supply networks require specific products to be buffered or kept. This indicates that a company's warehouses are crucial to the efficiency of its operations. In order to reduce operating expenses, it is crucial to comprehend how warehouses operate inside. In a market that is fiercely competitive, unstable, and demanding, warehouses are essential to supply chain management. Modern supply chain concepts mandate that organisations reduce their inventory levels. Additionally, expensive resources like money, people, and information technology are needed

Key indicators, Transportation and storage (NACE Section H), EU, 2019

	Value
Main indicators	
Number of enterprises (number)	1 251 019
Number of persons employed (number)	10 448 964
Turnover (EUR million)	1 437 385
Purchases of goods and services (EUR million)	968 373
Personnel costs (EUR million)	331 597
Value added (EUR million)	510 298
Gross operating surplus (EUR million)	178 700
Share in non-financial business economy total (%)	
Number of enterprises	5.4
Number of persons employed	7.9
Value added	7.4
Derived indicators	
Apparent labour productivity (EUR thousand per head)	48.8
Average personnel costs (EUR thousand per head)	35.2
Wage-adjusted labour productivity (%)	138.9
Gross operating rate (%)	12.4

Source: Eurostat (online data code: sbs_na_1a_se_r2)

eurostat

Figure 3.4: Key indicators, transportation, and storage (NACE Section H), EU, 2019 . [55].

for warehouses. When market competition requires higher performance from the warehouses, organisations must continually improve the design and development of warehouses for distribution logistics.

Authors in [45] describe that warehouse can be divided into different levels and can be classified into different classifications.

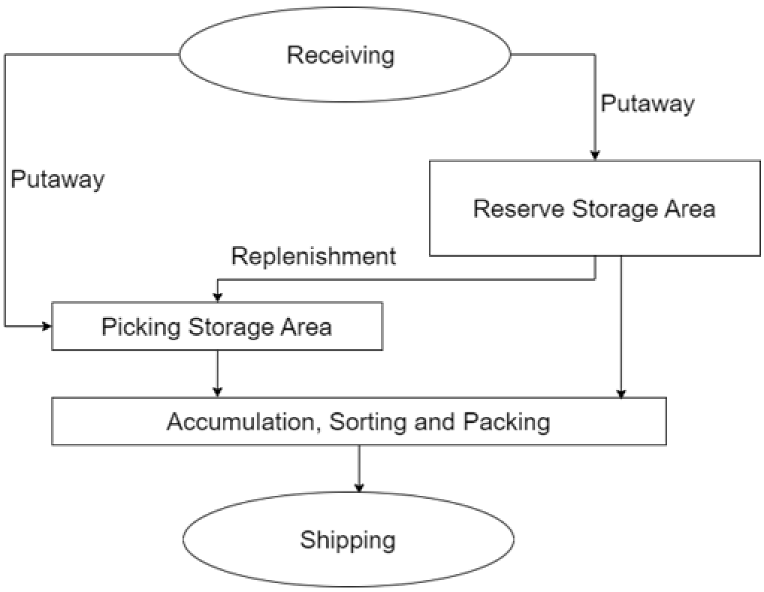


Figure 3.5: Typical Warehouse Functions and Flows. [45]

- Receiving and shipping - Two of the typical responsibilities of a storage business are receiving and shipping. Products are moved from the gates to storage spaces inside a warehouse by receiving operations. During shipping operations, items are transferred from the storage area to the loading zone into freight vehicles. Both the equipment picked out and the method of product transportation have a significant influence on both kinds of activities
- Storage - The storage function is concerned with organising the commodities to make the most use of the warehouse's resources. The three storage guidelines utilised in the warehouse are
  - Random storage policy: It enables a product's storage location to fluctuate or vary over time.
  - Dedicated storage policy: It designates a fixed location for each product's storage.
  - Class-based storage policy: It categorises items based on demand rates. Each class has its own section of the warehouse that is segregated for them. Here, the storage inside a space is haphazard.
- Order Picking - Order picking is the process of selecting and removing specific products in precise amounts from a warehouse to meet customer demands. Systems for choosing orders can be divided into several categories discussed in section 1.1.

3.3.1 Warehouse Layout

Authors in [52] describe various parts of a warehouse design. It may be broken down into three separate sections: the types of systems employed, the structure, and the rules that control all operational procedures. Product qualities must be considered when selecting the system. For instance, larger and heavier items often go on pallets in pallet racks, but smaller products could be put on shelf racks, which have a smaller storage capacity and take up less floor space. It is also discussed in [52] that each warehouse should adapt different layout in order to maximise its efficiency and target performance. A typical or traditional warehouse layout is seen in the figure 3.6.

The number of aisles, number of cross aisles that divide aisles into sub aisles, and number of blocks may all be used to specify the layout of the warehouse picking area. Depot is the place where a pickier goes to pick up the cart and then puts back all the products they have picked for shipment and packaging.

In [62] authors describe and discuss about other types of warehouses as shown in the figure 3.7. Due to the fact that the Bauer Gear Motor GmbH Esslingen design uses a standard warehouse structure with parallel aisle and cross aisle configuration, this work shall concentrate on this layout in this thesis.

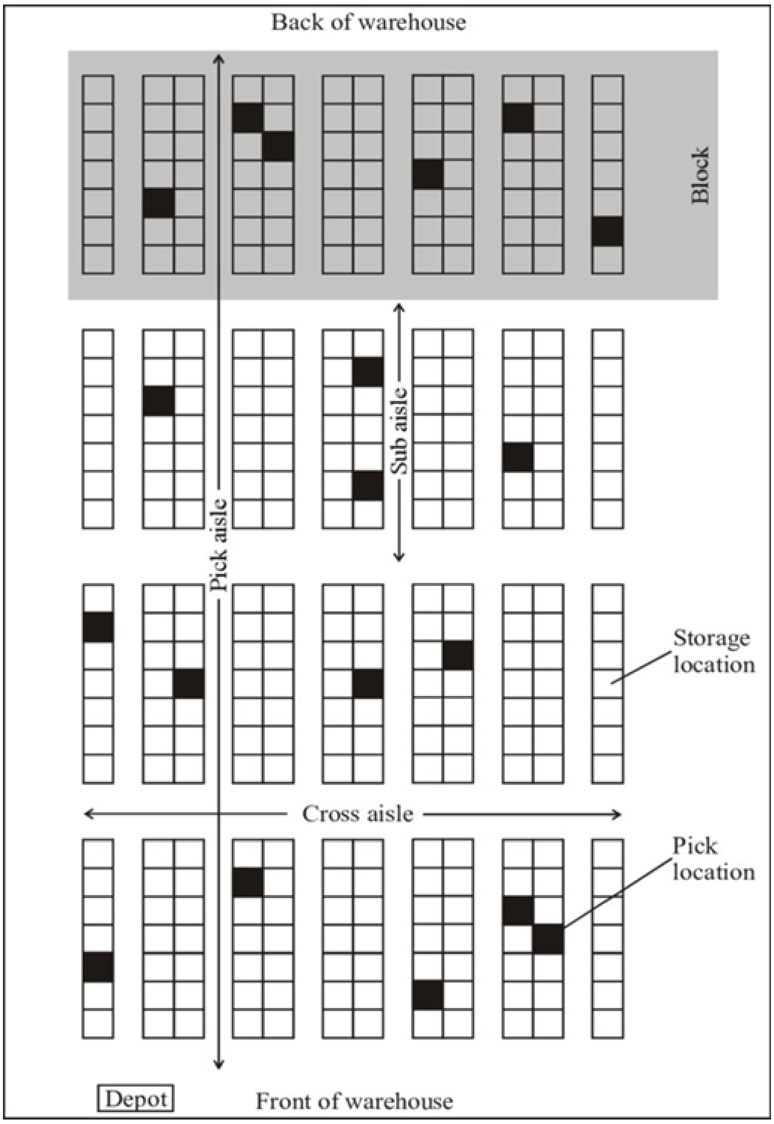


Figure 3.6: Traditional warehouse layout . [52]

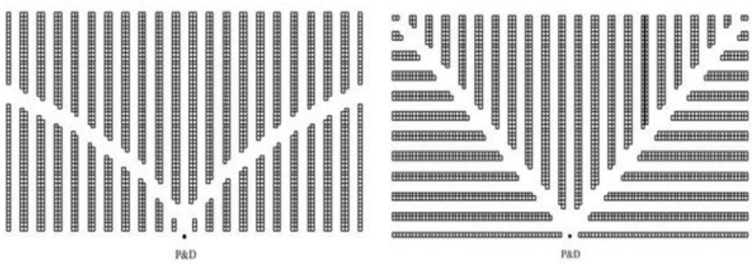


Figure 3.7: Flying-V (left) and Fishbone layout (right). [62]

3.3.2 Order Picking Process

In [20] and [17] authors describe those technical solutions that help the human order picking process are increasingly used in Order Picking System (OPSs). Different OPSs can be distinguished based on how much of the order selecting process is automated. Humans are used in manual order picking, and picker-to-parts The most manual OPSs may be grouped under OPSs. In turn, parts-to-picker systems combine automation technology, such as automated storage and retrieval systems Automated Storage and Retrieval Systems (AS/RS), which eliminates human duties like travelling, although picking (i.e., the retrieval of goods) is still done by hand in these systems. These programs are therefore regarded as manual OPSs. Last but not least, robot picking systems and automated picking systems automate the picking process by displacing human labour.

Pickers on a manual picker-to-parts order Prior to driving or walking across the warehouse to collect the items on a pick list, OPSs organise and arrange their duties. The main duties include walking while seeking for the item's location, gathering the required quantity of items, and documenting the selection. After finishing the select list, the order picker goes back to the depot to organise and box the items for delivery. Today's manual OPSs, such as picker-to-parts and parts-to-picker OPSs, which are still the most often used, are also receiving more technology assistance.

According to [50] a significant 2019 poll revealed that, at their warehouse, more than 50% of respondents depended on paper-based order picking, while just 14% employed pick-by-voice technology. In addition, just 15% of the respondents said they had installed AS/RS. IT administration tools, such warehouse management systems, were widely used (used by 85% of respondents), yet 58% of respondents collected data manually. Because they have less adaptability and flexibility to choose heterogeneous commodities, machine-based picking systems, in which order picking is carried out, for example, by robots, remain constrained in practise. Furthermore, robotic systems still require human intervention for troubleshooting. [38]

Therefore, it is plausible to assume that even with the growing trend toward automation, humans will still be needed for order picking in Logistics 4.0, especially given the development of e-commerce and the trend toward individualization with high-mix and low-volume warehouses. Because of increased technology use and increased human-technology connection, sociotechnical interactions in OPSs are significantly more complex.

Pickers have a variety of possibilities for communicating with automated or digital technical systems while utilising manual OPSs. Examples include manual picker-to-parts OPSs' AS/RS and pick to light system equipment. In addition to the established technology, wearable for information-providing systems like pick-by-voice or pick-by-vision aid order pickers in manual order picking. People interact with software components to plan, control, or process information on the shop floor or in a control room. In these circumstances, the role of the human becomes one of planning and supervision rather than of execution. Therefore, order selection must carefully handle a range of interactions, including taking into consideration Human Characteristics (HF).

HF (or ergonomics) is defined as "the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data, and methods to design to optimise human well-being and overall system performance" [37]. Workplace design has an impact on how well-being at work evolves. This also applies to choosing orders, which is typically seen to be extremely boring. Regarding perceptual, mental, physical, and psychosocial labour characteristics, employment should be realistic, bearable, sensible, and satisfying. Future work design must take into account human-technology interaction because it has been shown that Industry 4.0-related technologies might alter both job features and HF, as well as consequently employee outcomes like motivation or job happiness.

Both the derived components of OP 4.0, HF, and pertinent supporting or substitute technologies, as well as their interaction, must function well to improve system performance overall and achieve the objectives of Logistics 4.0. Therefore, HF are addressed by lessening the stressors that are put on people's perceptions, minds, bodies, and social relationships. Automation and digital technology replace and assist order picking tasks, which lower workloads and provide opportunities for diversity and motivation at work.

In [7] the author refers to travel time as a "Waste. It costs labour hours but does not add value". 3.1 gives us information about typical distribution of warehouse operating expenses

Function	% of annual operating expense
Picking	55 %
Shipping	20 %
Storage	15 %
Receiving	10 %

Table 3.1: Distribution of warehouse operating expenses. [7]

From table 3.1 there is a finding that in a typical warehouse management system the order-picking operation cost accounts for 55% which is more than shipping, storing, and receiving combined.

Table 3.2 shows us that order picking process can be broken down further into different activities.

Activities	Order-picking time (%)
Travel	50 %
Search	20 %
Pick	15 %
Setup	10 %
Other	5 %

Table 3.2: Order Picking Process . [7]

It is obvious that travel charges make up the majority of order picking costs, which are themselves the most expensive portion of warehouse operating costs. These numbers lead us to the conclusion that a significant issue warranting serious study is minimising the travel distance upon receiving a pickup order. Travel time can be reduced by planning the order picker's entire journey distance throughout a picking tour. An order picking problem is a specific subclass of the TSP - Steiner Traveling Salesman Problem that describes such an issue at a warehouse [20].

3.4 Routing Strategies Used in Warehouse for Order Picking

The order in which these sites must be visited must be decided once the picker has identified the objects that must be selected in a single trip and their related storage locations. A routing technique determines this order. The duration and travel time of the excursion are directly influenced by the chosen routing plan.

In [51] author describes various warehouse routing techniques such as S-shape, return, midpoint, largest gap, and composite strategy heuristics which are currently used in manual order picking in various warehouses.

- S-shape: When employing the S-shape strategy, the aisles carrying objects are entirely traversed in a single direction. This is done in the form of an S-curve. When employing this technique, it is important to distinguish between single-sided picking and two-sided picking. Single-sided picking is only desirable when there are several items to be checked inside the aisles or when the aisles are relatively large. Figure 3.9 shows us the S-shape routing strategy with single sided and two-sided picking.

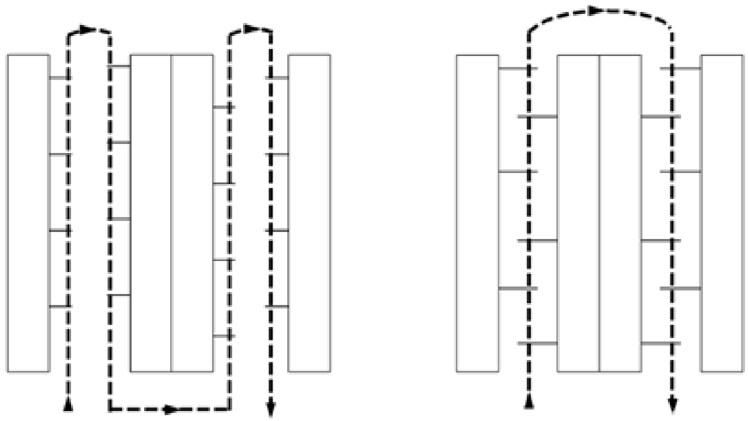


Figure 3.8: Single-sided picking (left) and Two-sided picking (right). [51].

- Return: When utilising the return technique to pick the items in this aisle, the aisles are always approached from the front and left on the same side. Only when there is only one option for changing aisles in the warehouse can this strategy be used. If the warehouse has two (front and rear) or more options for moving aisles, this technique will work almost as well as the other methods mentioned. Figure 3.10 shows us the return routing strategy.
- Midpoint and largest gap return strategy: Both the midway return method and the largest gap return technique include the order picker moving down the aisle, but the picker always ends up back at the aisle head where he began. The midway of the aisle or the distance with the greatest difference between two sequential item positions serves as the point of return in the aisle. Between such item locations, the greatest distance is not covered. Figure **??** shows us the midpoint and largest gap routing strategy.

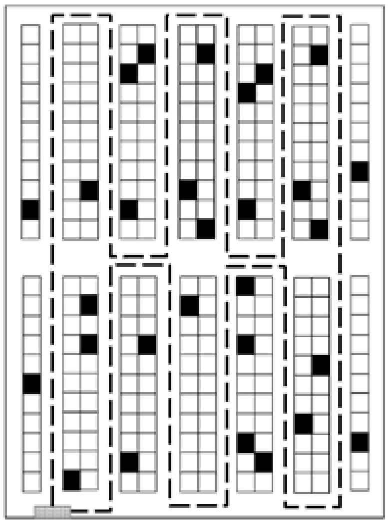


Figure 3.9: S-shape algorithm. [51]

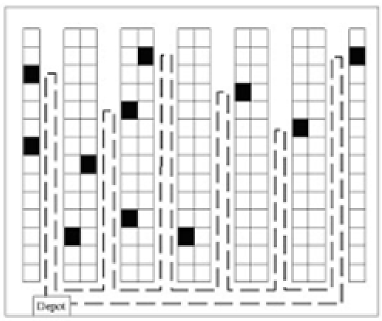


Figure 3.10: Return algorithm. [51]

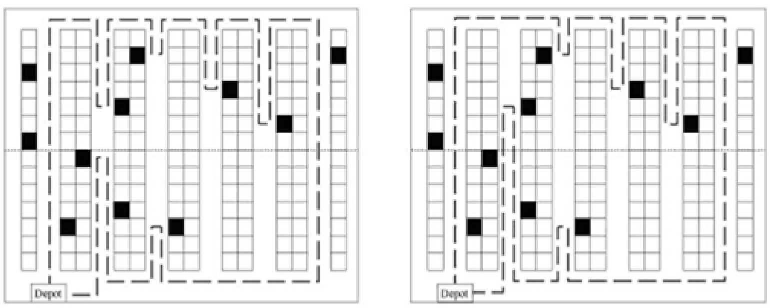


Figure 3.11: Midpoint algorithm (left) and Largest gap algorithm (right). [51].

- Composite strategy: This one combines the Transversal and Return routing strategies. This method assesses if it is quicker to go down each aisle in its entirety or to do a round-trip for each individual aisle. Figure 3.12 shows us the composite routing strategy.

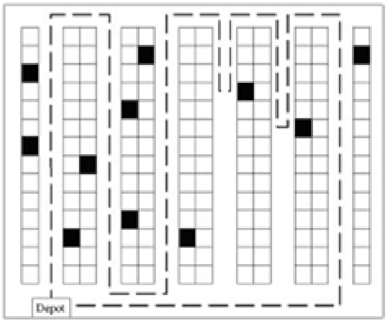


Figure 3.12: Composite algorithm. [51]

The approaches discussed above place restrictions on all possible designs for an optimum route. For instance, order pickers must walk the whole length of each aisle when using the S-shape approach. To identify the shortest way conceivable, a strategy has to be made that can take into consideration all plausible paths in and between aisles. Consequently, this work delves deeper into this subject and examine the TSP and STSP in order to get the best possible outcome.

3.5 Combinatorial Optimization Problems and NP-hard Problems

The field of combinatorial optimization addresses discrete decision-making issues. The best option must be selected from a limited or countably infinite number of possibilities based on some quantitative criterion. The majority of well-known combinatorial optimization problems fall within the category of so-called NP-hard problems and are inherently highly challenging to compute. Combinatorial optimization challenges are what is referred to as our warehouse routing issues. Problems in combinatorial optimization are ones where an ideal solution must be chosen from a limited number of options.

In [31] author states that the combinatorial optimization problems are divided into two parts.

- *The search variant – given a problem instance, find a solution with minimal (or maximal, respectively) objective function value.* [31]
- *The evaluation variant – given a problem instance, find the optimal objective function value (i.e., the solution quality of an optimal solution).* [31]

Thanks to recent advances in cutting-plane approaches, branch and cut, branch and bind, local search, and meta-heuristics as well as advancements in computer technology, combinatorial optimization may now be used to solve a wide range of real-world problems. Many combinatorial optimization problems, however, are computationally intractable. As a result, a workable approach to solving such problems is to use heuristic (approximation) algorithms to find approximately ideal answers quickly.

Any computing issue that falls within the category of NP-complete issues has yet to find an effective solution algorithm. This category includes a number of important computer science issues, such as the travelling salesman problem, satisfiability issues, and graph-covering issues. [39] In [57] author proves that TSP belongs to the class of NP complete problem. TSP and STSP are further discussed in the section 3.6.

3.6 Travelling Salesman Problem

The TSP is significant because it is an example of a wider category of issues known as combinatorial optimization problems. The TSP problem is a member of the NP-complete class of combinatorial optimization issues. In particular, effective methods might be developed for all other NP-complete problems provided one can solve the travelling salesman problem efficiently (i.e., in polynomial time). But nobody has yet developed a polynomial-time method for the TSP.

The following scenario is where the term “travelling salesman issue” originated. A salesperson must travel precisely once to each place, starting in his hometown, before returning home. He is aware of the distances separating each pair of cities, and he must choose the best sequence to visit them in order to minimise his overall trip mileage.

The travelling salesman’s situation is comparable to that of an order picker at a warehouse. The order picker leaves his home city (the depot), travels to each city (a node), and then returns to the depot.

In [30] the author mentions that the TSP has received a lot of interest from mathematicians and computer scientists because of how easy it is to understand yet difficult it is to solve. Author also mentions that *“the problem can simply be stated as: if a traveling salesman wishes to visit exactly once each of a list of m cities (where the cost of traveling from city i to city j is C ij) and then return to the home city what is the least costly route the traveling salesman can take?”*. [30]

More information on this topic can be found in research paper published by Hoffman and Wolfe (1985) [29].

In [25] authors tried to solve the issue of Homer’s Ulysses trying to make exactly one trip to each of the places mentioned in The Odyssey is known as the 16-city travelling salesman dilemma. The method of brute force produced 653,837,184,000 different paths. On a strong workstation, it took 92 hours to count all of these round trips in order to determine the shortest one. Successful algorithms for the TSP issue have been able to eliminate the majority of the round trips without ever explicitly taking them into consideration.

The following is the standard version of the travelling salesman issue as stated in [18]:

Variables are defined as x'_{ij} for each pair of products: $\forall i$, j $\in R$

$$x'ij = \begin{cases} 1, \text{if the tour uses the arc (i j)} \\ 0, \text{Otherwise} \end{cases} , \qquad Min \sum_{i,j \in R} d_{ij} x'_{ij} \tag{3.1}$$

$$\sum_{j \in R} x'_{ij} = 1, \qquad \forall i \in \mathbb{R} \tag{3.2}$$

$$\sum_{j \in R} x'_{ji} = 1, \qquad \forall i \in \mathbb{R} \tag{3.3}$$

$$x'\left(S:\overline{S}\right) \geq 1, \qquad \forall S < R : 2 \leq |S| \leq \frac{|R|}{2} \tag{3.4}$$

$$x'_{ii} \in N, \qquad \forall i, j \in \mathbb{R} \tag{3.5}$$

The order picker must visit each product precisely once and depart from them exactly once in accordance with constraints 3.2 and 3.3. These two restrictions, however, are insufficient to ensure that the model's output follows a single path. The order picker must transit from one subset to its complementary at least once for every partition into the two subsets S and S, according to constraint 3.4. Depending on whether $d'_{ij} = d'_{ji}$ (i.e., the cost of travelling from A to B is the same as travelling from B to A) exists, the TSP may be divided into two basic types: the symmetric TSP (STSP) and the asymmetric TSP, Asymmetric Travelling Salesman Problem (ATSP). In this study, the symmetric TSP is the only object of attention. Furthermore, since the Metric TSP is the focus of every TSP study in this thesis, it satisfies the triangle inequality.

$$C_{ij} \leq C_{ik} + C_{kj}, \forall (i, j) A, \forall k \in V, k \neq i, j \tag{3.6}$$

3.7 Steiner Traveling Salesman Problem

The order picking problem can be formulated as a special case (Steiner) of the TSP. Two distinct research teams introduced the STSP in the same year and can be looked in [13] and [23] for detailed information.

The STSP builds upon the conventional TSP in two different ways. On the one hand, the completeness of the underlying network is not assumed. As a result, there might not always be an edge connecting every pair of vertices. On the flip side, certain network nodes could not have any demand. However, certain non-demand vertices might need to be visited to connect two demand vertices served consecutively by a route. This implies that the collection of vertices that must be traversed to establish a feasible route is unknown in advance.

The STSP is relevant in both theory and practise because it better fits real-world applications like warehouse routing challenges where the network is incomplete and where, moreover, not all vertices in the network or graph must be visited.

A graph $G = (N, A)$ with the node set $N = S \cup R$ and the edge set A can be used to depict the issue. The depot, represented by node 0, and all n order items that need to be picked up at the warehouse are included in the node subset $R = \{1, \ldots, n\} + \{0\}$. The Steiner nodes denoting all p "crossing nodes" across two or more aisles are included in the node subset $S = \{n + 1, \ldots\ldots, n + p\}$, where p is the product of the number of cross aisles and the number of pick aisles in the warehouse. Every route between order items and the depot is represented by edge set $A \in R \times R$.

The warehouse in the below image with five pick lanes and three cross aisles (p = 15) that must be traversed to choose 10 goods and reach the depot location (n = 10) serves as an example of the idea. All nodes that expressly need to be visited at least once because they are either an order item or the depot are thus included in the node subset $R = \{0, 1, \ldots, 9, 10\}$. It is not necessary for the Steiner nodes in $S = \{A_1, A_2 \ldots, A_{14}, A_{15}\}$ to be on an order picker's route. They could, however, be visited while visiting nodes in R due to the unique (rectangular) construction of the warehouse.

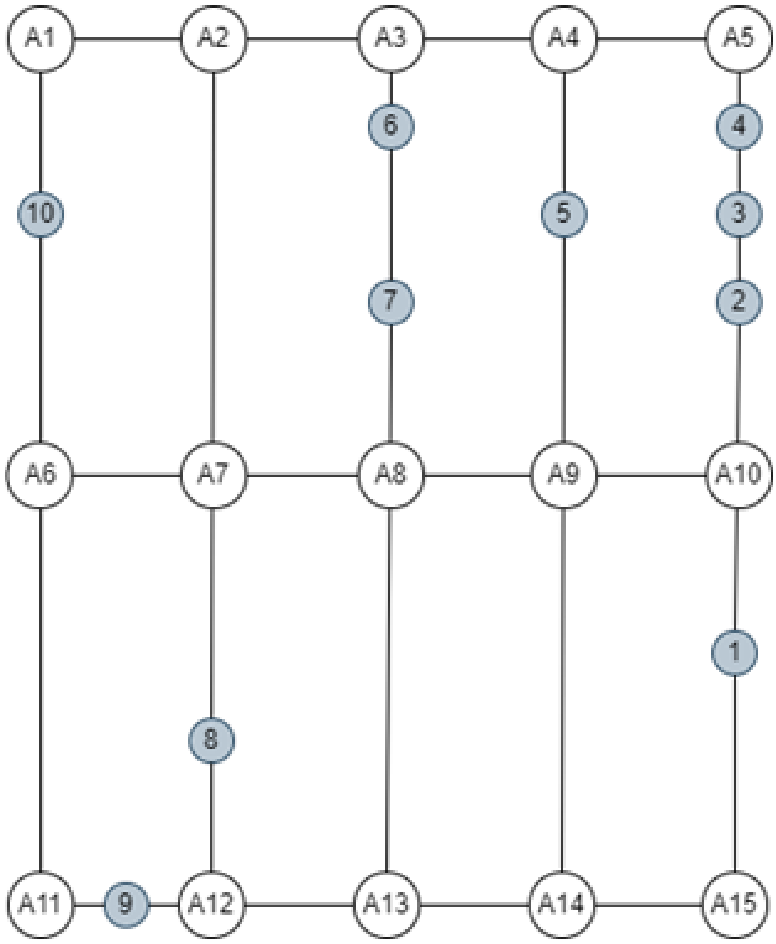


Figure 3.13: Example of STSP with traditional warehouse layout.

4 State Of The Art

This section provides the following information on the topics various techniques used to enhance the warehouse's order-picking procedure and how routing algorithms perform in the warehouse. Various papers and their work have been discussed which aim at the same objective to increase warehouse order picking efficiency process and also use similar technique.

4.1 Improving Efficiency Of Warehouse Order Picking

Since order selecting takes the most time, the warehouse's main objective is to improve it and difficult task to do in a warehouse and has a significant influence on the whole supply chain process. By increasing the effectiveness of the warehouse order picking procedure, several writers have found a chance to enhance the supply chain process. Thus, this section goes over earlier research on the subject.

The authors of [61] discuss a novel "pick and pass"technique that may be implemented to cut down on the time required to pick goods from an order list. The authors state that there must be a horizontal aisle for pickers to use when selecting components, and that each order must be divided into precisely as many parts as there are pickers available. The bound cavities determine the division order. The biggest space between two items is referred to as a bound cavity. Author also discusses that there is significant decrease in picking time of the orders by adapting this method for warehouse order picking. Figure 4.1 shows us an example of pick and pass system approach mentioned in [61].

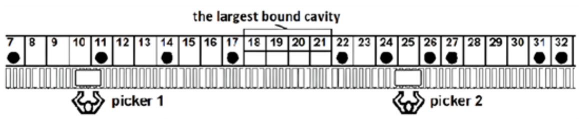
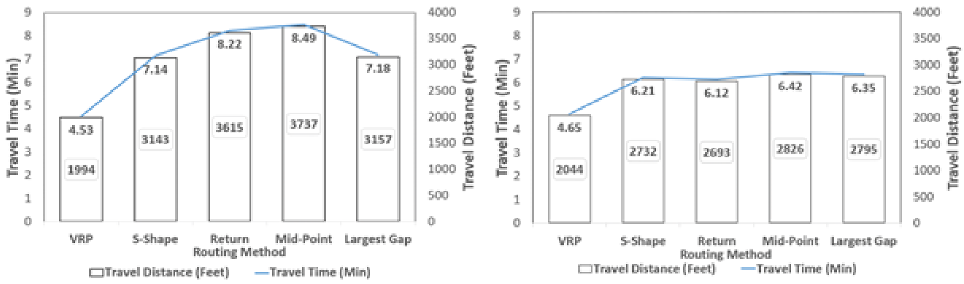


Figure 4.1: Order picking with pick and pass system. [61]

The research paper "Vehicle routing and simulation-based route optimization for warehouse order pickup activitie" [53] discusses how to improve the order picking process by implementing the Vehicle Routing Problem (VRP) algorithm in a conventional warehouse and contrasting it with the current routing methods described in chapter 3. The authors of this study article also discuss the benefits of VRP over the current routing techniques employed by conventional warehouses. The fact that VRP provides superior solutions in a small number of circumstances is also noted in this study. In other situations, the S-shaped routing method works better than the VRP algorithm, and the author advises using this technique when VRP cannot be used. Authors have also combined different strategies and compared it against each other. Figure 4.2 shows us the comparison between different routing strategies.



(a) Scenario 1 **(b)** Scenario 2

Figure 4.2: Comparison of travel distance and time for routing policies. [53]

Pick-by-light system as mentioned them in the earlier chapters has been used in many factories and warehouses as an aid for the pickers to their picking process. Pick-by-light system is installed and used by warehouses around the world to enhance the order picking process, overall efficiency and reducing picking error rates. In [56] authors discuss about the efficiency and the effect of the pick-by light system has on the pickers. Pick-by-light in this sense refers to a process in which shelf-mounted light signals direct the picker to the pick spot. Situation Awareness (SA), which is discussed in this paper, is defined as the capacity to recognise environmental influences over a wide range of time and place, comprehend their importance, and forecast the way they might act in the coming years. A comparative analysis has been made in this research paper based between pick-by-light system and paper-based pick list. In this study 31 subject cases were involved in this experiment. After conducting the experiment and analysis, authors conclude that paper-based system was better in terms of situation awareness and vision tunnel. Subjects were more aware of their surroundings and their heart rate was also lower while using this method. Although from the analysis it can be conclude that paper-based system put a bit more strain on subject compared to pick-by-light system. Overall, it was clear that pick-by-light system was not a necessary option to replace a paper-based system. Figure 4.3 shows us the comparative study between Pick-by-Paper (PbP) and Pick-by-Light (PbL) system.

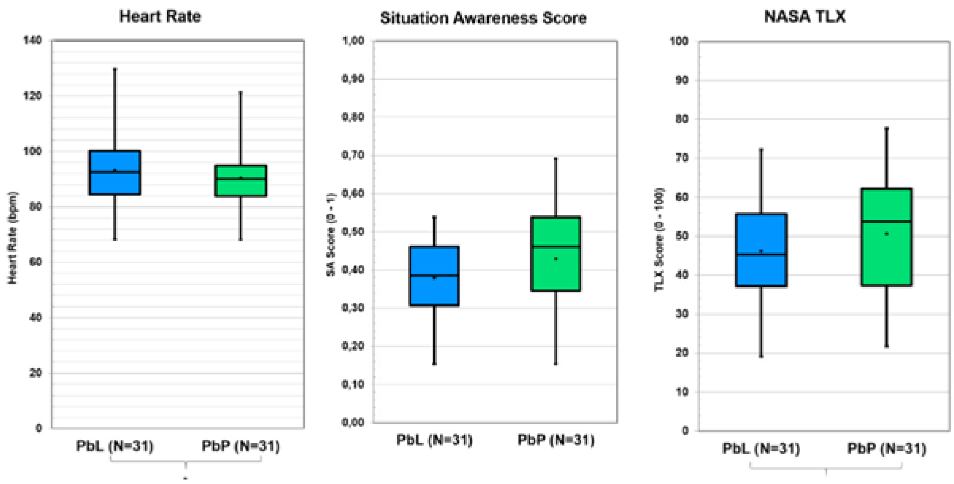


Figure 4.3: Boxplots for the dependent variables of the study: Heart rate is shown in the left diagram, Situation Awareness score in the middle and NASA TLX score on the right side. [56]

Pick-by-Voice Pick-by-Voice (PbV) system is a pretty new technology and a great enhancement in the are of order picking. Many companies and warehouse managers are thinking of using this technology to boost their order picking process and give more comfort to their pickers. In [15] the research paper carries out an analysis between pick-by-voice system and pick by terminal system. Pick by terminal system can be described as a permanent device attached to the picking cart (e.g., scanners or a screen with instructions). Analysis carried out in [15] gives us a good idea that there is a lot of improvement which needs to be carried out in the field of pick-by-voice system. The study demonstrates that using a pick-by-voice system results in somewhat less work autonomy than using a Pick-by-Terminal (PbT) method. The study also shown that pickers have more autonomy and may plan their picking tasks on their own. When pickers used the terminal system, which provided clearer and better information than pick-by-voice, there were also fewer picking mistakes. In light of the study's findings, it can be said that picking by terminal is preferable since it has a lower picking mistake rate and more degree of freedom. Additionally, pickers should not use any equipment throughout the whole picking procedure as it interferes with their comfort. There is an opportunity to improve in this area because research revealed that pick-by-terminal systems moved more slowly than pick-by-voice systems. Figure 4.4 shows us a typical pick-by-voice system setup with a picker.

Figure 4.4: Pick-by-voice system. [43]

Virtual reality is gaining popularity in today's society and has undoubtedly entered the realm of logistics and order picking. Research paper "Pick-by-vision: augmented reality supported order picking" as stated in [49] investigates the new technology of pick by vision system. Study in this research paper promises us the benefits and effects of increasing the efficiency of the order picking process. In this research paper authors have implemented the concepts of augmented reality on the head mounted display with virtual retinal display. In the developed system details of the order to be picked up is displayed is displayed on the retina display. Author explains the advantages of adapting this system as very little training is needed for the new pickers, picking error rate decreases significantly as the bin is highlighted as shown in figure 4.5. Author also explains that the pickers have higher degree of freedom compared to paper-based picking system. As every system has its advantages there are downside of this approach too as pickers are not so comfortable wearing the proposed hardware all day. Time taken to pick orders with this new system is almost similar compared to paper-based system. There is no significant improvement is time reduction to enhance the efficiency of order picking process. Author also mentions that this new technology is still in research phase and need a lot of improvement to make this technology a reality. It is still far away from coming into reality and being a wearable object in day today operations. Figure 4.6 shows us comparison of pick by vision technology against paper-based systems.

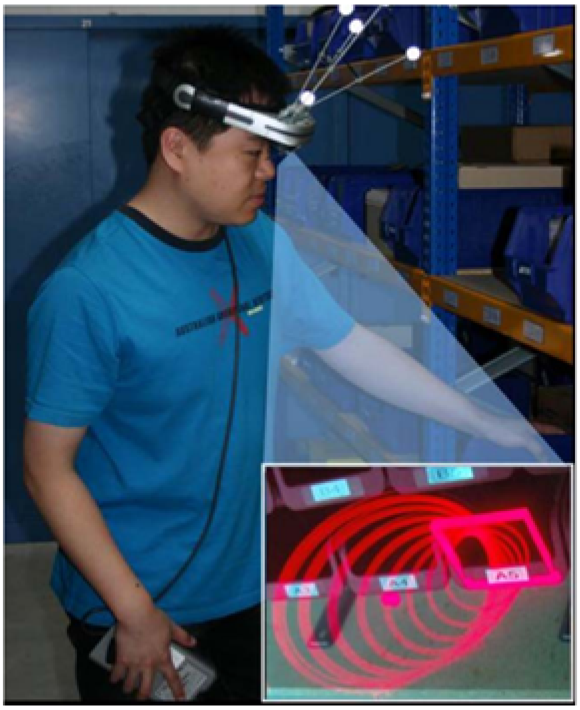


Figure 4.5: Pick-by-Vision system with tracking and the visualization of the tunnel. [49]

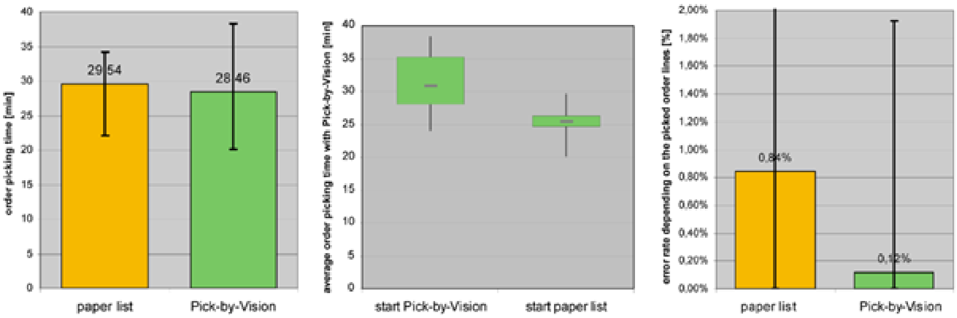


Figure 4.6: Mean values of the picking time (left), difference in order picking times due to the starting technology (middle), mean values of the picking errors (right). [49]

"Order-picking Methods and Technologies for Greener Warehousing" [21] is a research article that explains how warehouses are becoming more effective and going toward a greener approach. The author lists many strategies for creating a green warehouse, including the use of paperless warehouse administration, effective lighting and ventilation systems, better-insulating building materials, and machinery that uses less energy and emits less carbon. Out of all the mentioned options, author emphasizes on improving order picking process by adopting digital technologies such as pick-to-light, pick-by-voice and barcode/RFID scanners. Author also mentions that setting an appropriate routing system, storing and picking strategy, selecting the best picking technology, and choosing the most appropriate layout may all result in significant savings, making warehouse operations more productive and environmentally friendly at the same time. It may inferred from this study that there is a strong link between enhancing the order picking process via the use of digital technology and environmentally friendly warehouse operations.

4.2 Warehouse Order Picking Using Routing Algorithms

In [48] author describes a way to minimise the order picking distance by using “A solvable case of the traveling salesman problem”. In this research paper a new algorithm is introduced called Partial Tour Graph (PTS). PTS is used in a traditional rectangular and symmetric warehouse as shown in figure 4.7. In PTS the tour stars from the first node and finds any unused parallel arcs to visit the next node. Parallel arcs represent the paths between crossovers. If there exists any unused path in crossover, then the next node is visited. This process continues till all the pickup nodes are visited. Once all the nodes are visited then the tour ends. Author mentions that this is an efficient method to minimise order picking but not optimal. Author also mentions that this method gives results only for the warehouse shown in figure 4.7. If the layout is changed then or if there are more crossovers added between aisles, then the solution fails to give desired results. Also, it can said that this does not guarantee that it will get the shortest possible route. Figure 4.8 shows us the solution of PTS for the given set of nodes in figure 4.7.

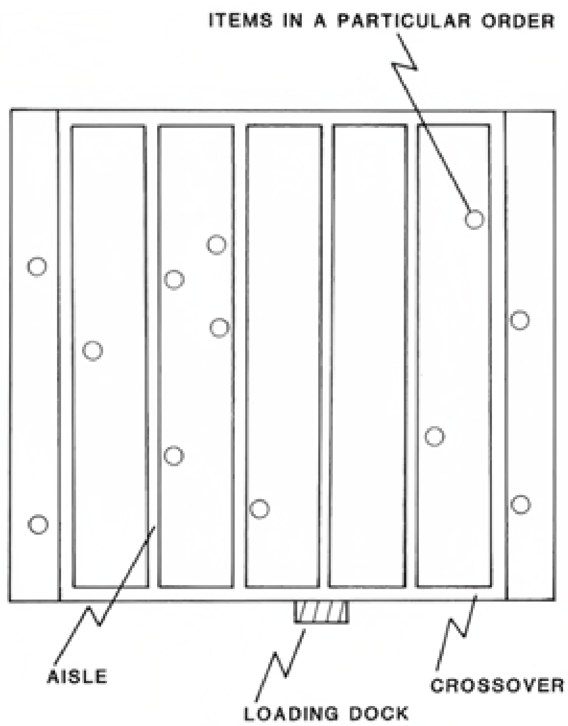


Figure 4.7: Traditional rectangular and symmetric warehouse. [48]

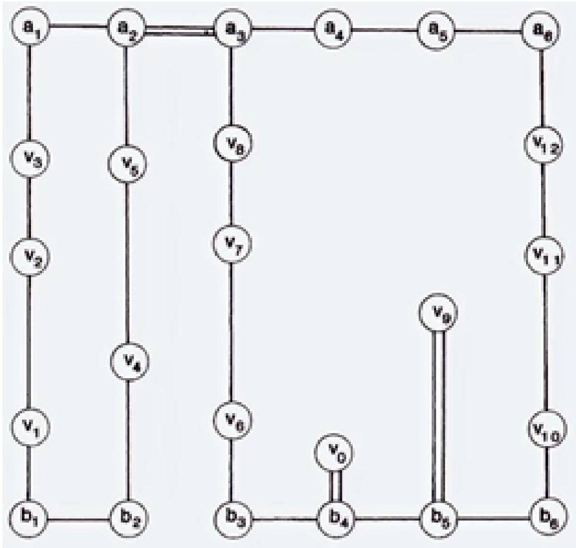


Figure 4.8: Optimum order-picking tour. [48]

In [41] author describes compares the S-shape heuristics as mentioned in chapter 3 and with the optimal solutions. The optimal solution is same as mentioned in [48]. Author mentions the benefits of using optimal solutions over S-shape heuristics as it almost 11 % to 14 % reduction in total time of picking process.

In [58] authors investigate and compare different traditional routing heuristics such as S-shape, largest gap, combined and LKH. From this research paper it is said that the Steiner TSP problem-specific properties may be used by current specialised construction methods, but their one-dimensional nature is too constrictive. Block-by-block solutions are built using the S-shape, greatest gap, and integrated heuristics, although pick-by-pick aisle works, aisle-by-aisle. They are similar in that they do not contemplate incorporating order items from a different block (or pick aisle) into the current block's incomplete sub route. By doing this, they drastically limit the solution space's investigated region and are prevented from arriving at a large number of possibly superior solutions. Due to the stated reasons authors implements 2-opt algorithm with LKH to give better results. Figure 4.9 shows us the performance of various approaches and reduction in travelling distance.

In [51] authors discuss about how branch-and-bound algorithm works and gives provides with the result which is used to generate shortest routes for order picking process. Performance evaluations of heuristics and the branch-and-bound technique for various warehouse layouts and order sizes are done.. According to the author, the combined+ heuristic outperformed the other heuristics for the vast majority of the conditions examined in the study. When there were two cross aisles and few picks, it was found that the widest gap was favourable. Furthermore, author compares the optimal solution with branch and bound approach and concludes that the gap between this optimal routing method and branch and bound varies substantially. In [46] author mentions that "The branch-and-bound downside is its inconsistent run-time behaviour, which makes it unsuitable for practical implementation".

In [40] authors two approaches for finding the shortest path for order picking process. The research paper aims on two approaches which are shortest path problem and the traveling salesperson problem. This paper discusses application of Dijkstra's algorithm to find the nearest neighbour

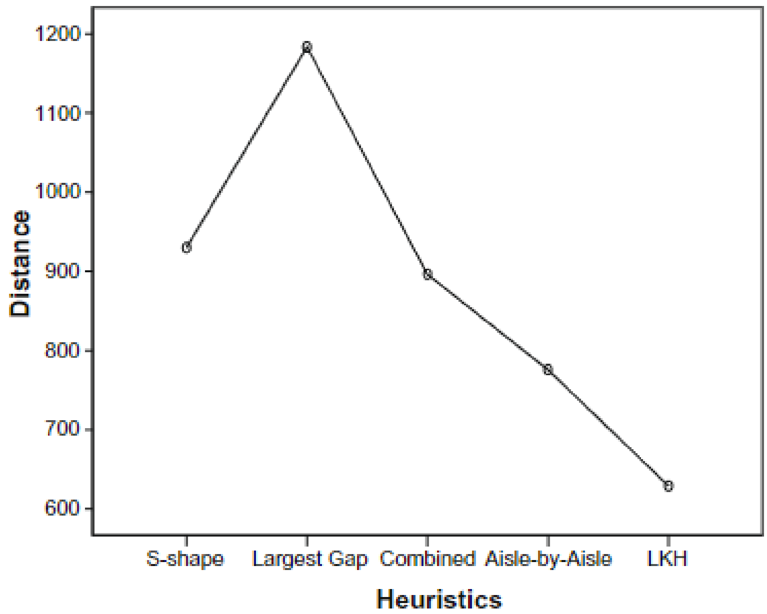


Figure 4.9: Average performance of heuristics. [58]

for shortest path problem and nearest neighbour heuristic for travelling salesman problem. Author mentions that there is a significant reduction while using the program developed mentioned in the paper. Downside for using the developed program is lot of manual work to enter the vertices and values in adjacency matrix. Due to this, proposed application cannot be used for real life scenarios. Author also mentions that the proposed solution does not offer any degree of accuracy with respect to optimum tour. Future scope of this paper discusses to implement Christofides' algorithm which guarantees the tour to be within 1.5 times of the optimum tour [11].

4.3 State Of The Art - Overview

From the sections 4.1 and 4.2 it has come to light that previously research and development has been carried out regarding the main objective of this thesis is to optimize the order picking process in a warehouse. In the following points, we try to summarise the proposed work in this thesis extends the base ideas and meanwhile presenting the contributions of this thesis work:-

1. As discussed in [61] the "pick and pass" technique is suited for horizontal single aisle with a conveyor belt running besides it. Pick and pass technique uses largest bound cavity approach to reduce the picking time and processing the order but unlike the solution proposed, Bauer Gear Motor has a traditional warehouse layout with multiple vertical aisles which acts like a random storage policy for spare parts department. Hence this method is not exactly suitable for minimising the order picking process for the mentioned warehouse. This method also assumes to have at least 4 pickers which is not possible every time in a real case scenario.

2. In [53] the objective to optimise order picking process is solved by using Vehicle Routing Problem VRP approach. Vehicle routing problem basically provides solution to minimise the picking distance by using more than one resources (e.g., robots, automated vehicles, or

pickers with carts) From this study it is clear that the proposed solution performs better than other existing routing techniques used by warehouses. Downside of this problem is also explained in [53] that when in case of large quantity of pickup points, VRP does not give a better result than the S-shaped heuristics. Hence there is a good scope to find a near optimal solution which gives us the shortest path in all given conditions.

3. Many researchers and companies have investigated and implemented pick-by-light system to improve the order picking process. Pick -by-light system work great with horizontal aisle and not with vertical aisle. If the picker has to pick through multiple vertical aisles, then he has no idea where the next pick-up point is and he will spend roaming the whole facility. This will not yield good result in any given scenario to reduce the picking time. Also, in [56] a detailed study has been carried out between paper-based system and pick-by-light system. Study shows that pickers using pick-by-light system need to concentrate more on the lights which are lit up which in return increases their hear rate. Pickers are also not aware of their surrounding which is a major breach in the safety of the warehouse. Hence there needs to a better digital solution where pickers are aware of their surrounding environment, and they are not stressed.

4. Another solution is proposed in [15] which uses pick by voice system to enhance the productivity of order picking in warehouse. Advantages of this solutions is hands free operation of pickers. Downsides for pick by voice systems are high initial investment and monotonous instructions from the headset. Comparative study performed in [15] gives us an clear idea that pickers have more work autonomy when they used a digital device to pick items compared to pick by voice system. Pickers were also bored and less concentrated while using pick by voice system due to continuous instructions given by the headset. From this study it is clear that pickers would be benefited more from a digital system which they can carry or is placed on their cart.

5. Latest technology which is still into research phase is pick by vision. This system uses concepts of AR which displays the path and items to be picked up on the retinal display attached to headset. As per study conducted in [49] using pick by vision over pick by paper list does not yield any benefits in terms of reducing picking time of an order. Also, average picking time for an order is considerably higher than pick by paper. Only advantage implementing pick by vision is error rate of picking items from orders is lowered by considerable rate. From this study it is clear that if picker is given some kind of visual aid, picking error rate will decrease and all hidden costs to replace the correct item will be avoided.

6. In [48] and [41] authors do not discuss about any new technology rather they discuss and investigate about providing with the shortest path for pickers using an optimal algorithm. Simulations are carried out and compared against S-shaped heuristics. Authors in [41] mention that there is about 11 % to 14 % reduction in traveling distance compared to earlier used practices. Though this approach provides with a reduced distance but does not provide any guarantee if it close to optimal solution. Hence there is still scope to investigate into more algorithms and achieve a solution which is closest to optimal.

7. There has also been research on LKH and concored in [58]. LKH and concorde is compared again with existing routing techniques such as S-shaped, midpoint, return and composite. Author finds out that LKH gives the lowest cost route for maximum number of simulations.

8. In [51] author implements shortest path problem and TSP heuristics nearest neighbour algorithm and concludes that it gives better solution compared to existing practices. Although this approach provides a shorter route but does not guarantee any degree of accuracy with respect to optimum tour. Author also mentions to implement Christofied's algorithm which has proved to give a tour within 1.5 time that of an optimum tour.

After looking at all the points mentioned above, gaps mentioned in points 1-5 calls for a system which is digital, gives more degree of freedom, provides visual aids and keeps pickers aware of their surroundings. Points 6-8 calls for more study of TSP heuristics and compare their results for the given use case. Overall, the proposed solution provides a digital terminal placed on a cart with providing the shortest path by comparing various TSP heuristics with providing visual aids. Proposed solution also aims to eliminate the paper based system which in turn will make the warehouse operations more greener and efficient as mentioned in [21].

5 Design Strategy

An overview of the design approach used to create the proposed solution is provided in this chapter. According to the research gap stated in the chapter 4.3, the suggested solution provides a digital paperless option that enables customers the almost ideal path to pick up their purchases. The system's general flow and expected outcomes are discussed in the first section. The TSP heuristics that have been selected for this thesis' investigation are described in more detail in the second parts.

5.1 Overview Of The Proposed System

All the points discussed in chapter 4 are the basis for this proposed system. The proposed system offers a digital platform which can be used on any windows platform (scope limited to the prototype) and further to be expanded on other platforms like Android or iOS. Prototype to be developed is a digital platform which can be used via a web server providing with the shortest route on the map of the warehouse. This prototype also provides clear and important information related to picking up orders such as order number, material number, location, description, and no. of quantities to be picked up. Figure 5.1 shows us the overall flow process of the proposed system in this thesis. Figure 5.2 shows us the expected outcomes form this solution.

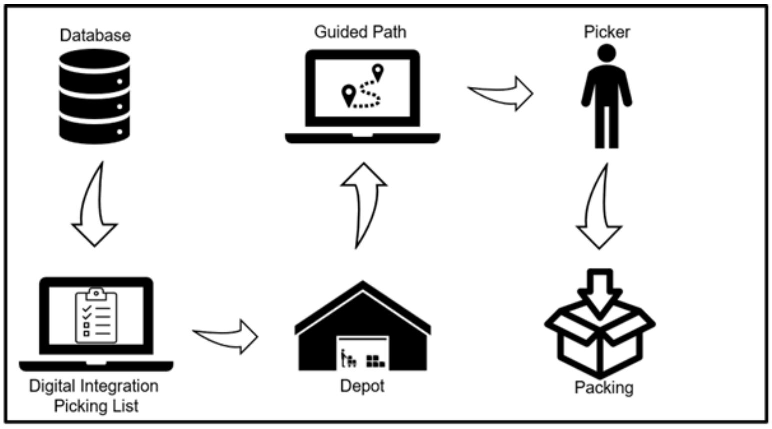


Figure 5.1: Process flow with digital platform for order picking.

As it can be seen in Figure 5.1, the proposed solution has to be interfaced with the existing Enterprise Resource Planning (ERP) system where there is a database for the orders to be collected and delivered. For the scope of this thesis, there is no direct connection between the live ERP system of the Bauer Gear Motor due to high stakes of the company's day to day operations. Instead orders for spare parts department is extracted from the Systems Applications and Products (SAP) system of

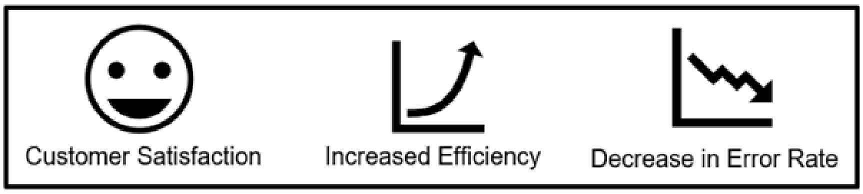


Figure 5.2: Outcomes from using the digital solution.

the company and stored it into a Comma Separated File (.csv) file which is then accessed by the system. As the picker enters the order number, which is to be picked up, a digital map is displayed of the warehouse with all the pickup point with highlighted path and directions from source or start point. Picker presses the next item button which shows him the details of the next item to be picked up with the picture of the item to be picked up. Addition to this the cell or the position is also highlighted on the map where the picker needs to go next. Picker can then follow the marked path to reach the next point to pick up the next item. Once the tour is finished picker comes and drops the picked items at the same point where he started.

With this system it is clear that the picker does not have to wear any gear on the body which can affect the comfort and concentration of the picker while picking. Picker can move hands free without any sort of paper or handheld devices which can hamper the order picking process. Visual aids in form of pictures and digital map increases the efficiency and decreases the picking error rate as it can easily be compared with the picture depicted. Pickers can be more aware of their surroundings and be safe from risky environment like forklifts, overhead cranes, unattended bins, and other pickers. Proposed system also gives picker more work autonomy in order to work more freely and independently.

As a result of adapting to this new solution the expected outcomes are as follows:

- Optimisation of order picking process as the system compares different routing algorithms which is discussed in next section and provides it with the shortest route. Hence overall travel distance for picking is minimised.
- Decrease in picking error rate as pickers can compare the item to be picked with the actual part which is to be picked up. Hence the hidden expenditure to replace the wrong shipped part can be avoided to a great extent.
- Increasing comfort for the laborious order picking process by eliminating the need to carry or wear any sort of list or devices.
- Reducing carbon footprints due to elimination of the paper-based list. Paper used to print the order picking list can be completely eliminated with new digital system.

5.2 Overview Of TSP Heuristics – Algorithms

From section 5.1 it can be learnt that many researchers and mathematicians have investigated various routing methods to reduce the walking distance and to find out the optimal route or the shortest path around the warehouse. Routing strategies like S-shape, midpoint, return, composite and classical

TSP have been heavily researched and researchers have come up with concrete results. From literature survey it is clear that TSP gives better results than other routing techniques. Hence this thesis focuses on less investigated TSP heuristics like greedy algorithm, nearest neighbour algorithm 2-opt algorithm, Christofied's algorithm, and LKH heuristic. Overview of these algorithms is provided in following sections.

5.2.1 Greedy Algorithm

As discussed in [14] a greedy algorithm is one that pursues a global optimum by picking the locally best option at each stage of the problem-solving process. A greedy technique typically fails to yield the optimal solution, even while a greedy heuristic which may produce locally optimum answers that strongly resemble a global optimal solution in a respectable period of time it does not guarantee an optimal or near optimal solution for the given set of data. Also, greedy algorithm chooses the starting point at random and looks for the next closes point. Following steps explains the working of greedy algorithm [14].

1. Calculate the distance matrix $[D_{ii}]\, i = 1, 2, 3, \ldots.k$, where k is represents the number of nodes. Figure 5.3 and Table **??** explains the distance matrix.

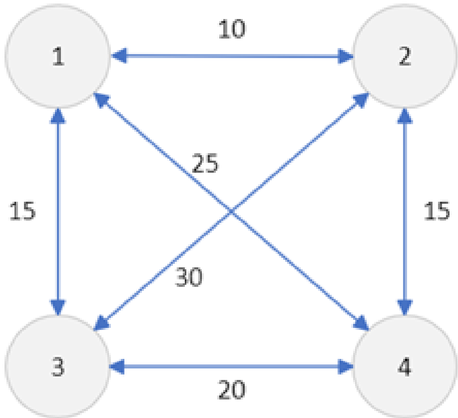


Figure 5.3: Random graph

Nodes	1	2	3	4
1	0	10	15	25
2	10	0	30	15
3	15	30	0	20
4	25	15	20	0

Table 5.1: Distance matrix from Figure 5.3.

2. Remove the column X from the distance matrix after selecting a base city at random and setting it to be X.

3. Set X as start of the tour.

4. Select the smallest value from the row X in the distance matrix.
5. Assign this least value as Y and include node Y in the tour.
6. Set Y = X and repeat steps 2 – 4 till all the nodes are added to the tour.
7. Once all the nodes are added to the tour, add the first selected node to complete this cycle.
8. Display the nodes in the tour and the associated distance travelled.

Greedy algorithm works basically similar to nearest neighbour but selects the starting point at random which is something not desired in the order picking process as position of the depot is fixed. Hence, in this thesis nearest neighbour algorithm instead of greedy algorithm is implemented and compared.

5.2.2 Nearest Neighbour Algorithm

The 1-opt operator is the fundamental operator of the λ-operators. Before all nodes have been reached, the algorithm will select the closest neighbour for each node, after reconnecting with the beginning node.

As explained in [26] another naive and modified greedy algorithm is the nearest neighbour heuristic. It starts at one fixed node and links to the next unvisited nodes. This is repeated until all nodes have been reached. After then, it returns to the starting node. The closest neighbour algorithm is simple to use and runs quickly with the time complexity of $O\left(n^2\right)$, where n is the number of nodes. but because of its "greedy"character, it occasionally overlooks shorter paths that are obvious to humans. Nearest neighbour algorithm follows the same steps as mentioned in the section 5.2.1, the only difference is that the staring and end node is fixed.

Following pseudocode helps us understand the working of algorithm in more detail. [44]

```
node = 0
visited = set()
while len(visited) < len(nodes):
    tour.append(node)
    visited.add(node)
    # Find the closest, non-visited neighbour
    next = find_closest(G[i], visited)
    node = i
```

Listing 5.1: Nearest Neighbour Pseudocode. [44]

5.2.3 2-Opt Algorithm

Most likely the most basic and often applied TSP local search heuristic is the 2-opt method. A straightforward improvement heuristic for the travelling salesman problem is the 2-Opt heuristic. It begins with an arbitrary tour and regularly swaps out two of its edges for another pair, as long as doing so results in a shorter trip. The algorithm reaches a local optimum where no more steps of improvement are conceivable. Time complexity for 2-opt algorithm is $O\left(n^2\right)$.

Finding a pair of nodes $(i\ andj)$ for which adding a new edge will reduce the cost of the tour is known as a 2-opt move. In other words, the algorithms replaces $(i, i+1)$ with (i, j) and $(j, j+1)$ with $(i+1, j+1)$. The advantage provided by this adjustment is calculated using the difference between the old and new edges. If the gain is favourable, new improved tour is considered. Equation 5.1 helps us understand the switch better [44].

$$g = c\,(i, i+1) + c\,(j, j+1) - c\,(i, j) - c\,(i+1, j+1) \tag{5.1}$$

The tour is left intact up until node i, its new neighbour (the tail of the selected edge), the tour between $(i+1\ andj)$ is added in reverse order, and the move is finished with the tail of j and the remaining portions of the original tour. Figure 5.4 shows an example of 2-opt swap.

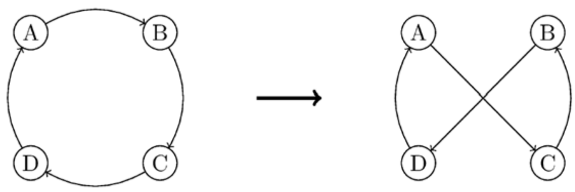


Figure 5.4: Example of 2-opt swap.

Following pseudocode helps us understand the working of algorithm in more detail. [44]

5.2.4 Christofide's Algorithm

A heuristic with a 3/2 approximation guarantee is the Christofide's algorithm. The worst-case scenario for the tour is that it is no longer than 3/2 the duration of the ideal tour. The Christofide's technique is frequently used to identify a nearly optimum path in a metric space because of its speed and 3/2 approximation guarantee. Time complexity for Christofide's algorithm is $O\left(n^4\right)$.

If the distances between the nodes is symmetric and adhere to the triangle inequality Christofide's algorithm can be used, which is on a typical x, y coordinate plane (metric space). It was published in 1976 and is still the best approximation ratio for metric space [11]. For detailed information and proof of 3/2 approximation ration please refer to [11].

Christofide's algorithm works as follows. Let $G = (V, w)$ be an instance of the travelling salesman problem. That is, G is a complete graph on the set V of vertices, and the function w assigns a non negative real weight to every edge of G. According to the triangle inequality, for every three vertices u, v, and x, it should be the case that $w\,(uv) + w\,(vx) \geq w\,(ux)$.

```
            while improved:
            best = c(tour) # start with an initial tour
            size = len(tour)
            improved = False
            for i in tour[0:size-3]:
                # i+2 because i+1 will be the tail of the edge
                for j in tour[i+2:size]:
                    # Calculate gain: old edges - new edges
                    gain = c(i, i+1) + c(j, j+1) - c(i, j) - c(i+1, j+1)
                    if gain > 0:
                        best -= gain
                        # i is the last element in place
                        tour = swap(tour, i + 1, j)
                        improved = True
                        break # return to while
```

Listing 5.2: 2-opt Pseudocode. [44]

Then the algorithm can be described in pseudocode as follows. [59]

1. Minimum spanning tree T of G is created.
2. Let O represent the collection of odd-degree vertices in T. O is said to have an even number of vertices by the handshaking lemma.
3. In the induced subgraph provided by the vertices from O, minimum-weight perfect matching M is produced.
4. The connected multigraph H is created by joining the edges of M and T, and each vertex has an even degree.
5. Eulerian circuit in H is created.
6. By skipping repeated vertices, the circuit is made into a Hamiltonian circuit from the step 5.

Following images shows us the working of the Christofide's algorithm.

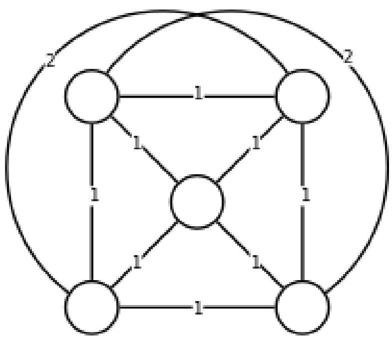


Figure 5.5: Graph with nodes adhere to triangle inequality. [59]

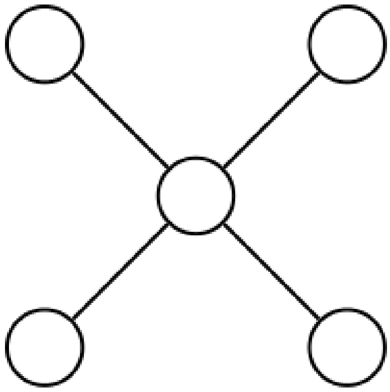


Figure 5.6: Minimum spanning tree for the graph in Figure 5.5. [59]

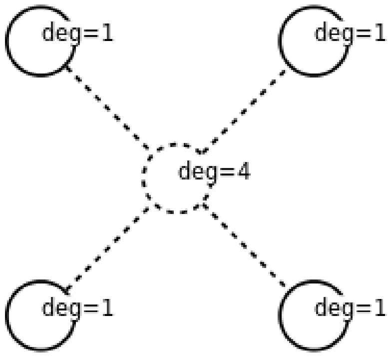


Figure 5.7: Nodes with odd degree. [59]

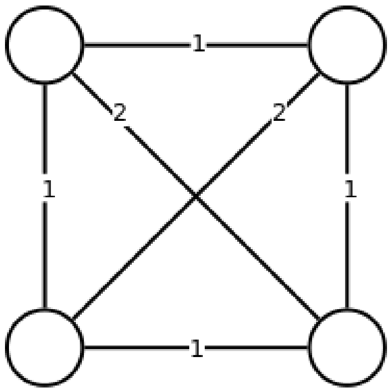


Figure 5.8: Subgraph of graph in Figure 5.5 with nodes in Figure 5.7. [59]

Minimum spanning tree: A connected, edge-weighted undirected graph that binds all of the vertices together, without any cycles, and with the least amount of total edge weight is known as a Minimum Spanning Tree (MST).

Perfect matching: In a graph, a perfect match is one that encompasses every vertex.

Eulerian circuit: Eulerian circuit is a route in a graph in which every node is visited exactly once and end on the same node where it is started.

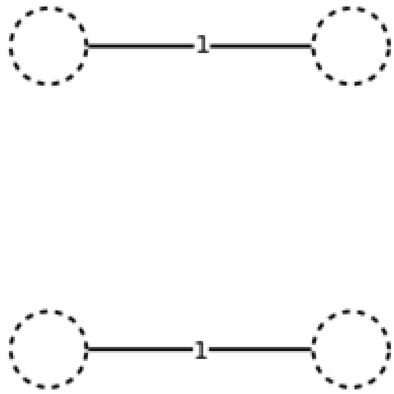


Figure 5.9: Minimum-weight perfect matching M. [59]

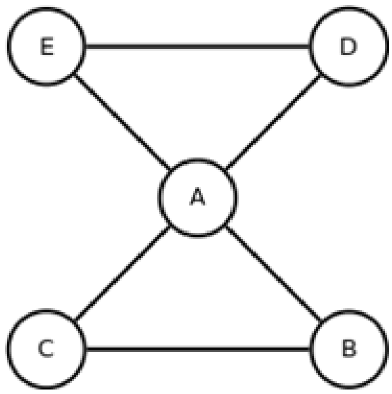


Figure 5.10: $T \cup M$ to form a Eulerian multigraph. [59]

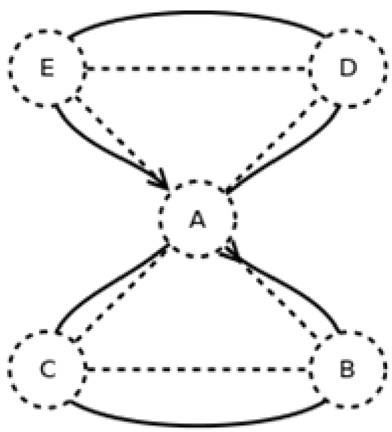


Figure 5.11: Euler tour is calculated. [59]

5.2.5 Lin-Kernighan Algorithm

Most people agree that the Lin-Kernighan heuristic [42] is one of the best techniques for coming up with ideal or almost ideal answers to the symmetric travelling salesman issue TSP.

As discussed in [28] The idea of "λ-opt" forms the basis of the "λ-opt algorithm"

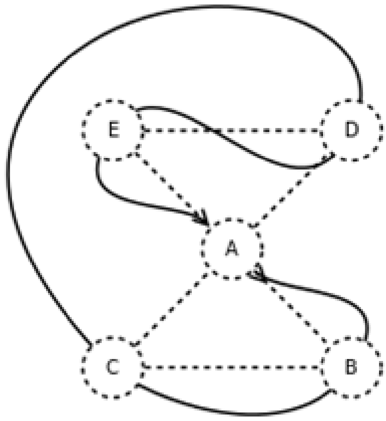


Figure 5.12: Repeated nodes are removed. [59]

If it is impossible to acquire a shorter tour by replacing any one of a tour's links with another set of links, the tour is said to be λ-optimal (or just λ-opt). Unfortunately, as the number of nodes rise, so does the number of procedures required to test all λ-exchanges. The testing of a "λ-exchange" has an $O(n\lambda)$ time complexity in a naïve implementation. Furthermore, the maximum number of λ-exchanges has no non-trivial upper bound. Therefore, the values$\lambda = 2$ and$\lambda = 3$ are the most often employed. By developing a potent variable λ-opt algorithm, Lin and Kernighan overcame this flaw. The method checks if switching connections might lead to a shorter route at each iteration step for rising values.

Tests are run to see if $\lambda + 1$ link exchanges should be taken into consideration given that the exchange of links is being thought about. This is repeated until a set of halting requirements are met.

The group of so-called local optimization methods includes the Lin-Kernighan algorithm [36] [35]. In terms of swaps (or exchanges) that can turn one tour into another, the algorithm is described. The algorithm starts with a viable route and continually makes trades that shorten the current trip until it reaches a tour for which no exchange produces an improvement. From the first tours that were produced in some way randomly, this procedure might be repeated several times.

As explained in the [28] here is the pseudocode for Lin-Kernighan algorithm.

1. A random tour is generated and assigned it as an initial tour T.
2. i = 1 is assigned, and we choose t_1.
3. $x_1 = (t_1, t_2) \in T$ is chosen.
4. $y_1 = (t_2, t_3) \in T$, such that $G_1 > 0$ is chosen. Jump to step 12 if condition is false.
5. i is incremented by 1, $i = i + 1$
6. $x_1 = (t_{2i-1}, t_{2i}) \in T$ is chosen, such that
    - The configuration that results is a tour T', if t_{2i} is joined to t_1.
    - $x_i \neq y_s$ for all values where s < i
7. $y_i = (t_{2i}, t_{2i+1}) \in T$ is chosen, such that

- $G_1 > 0$.
- $y_i \neq x_s$ for all values where s <= i.
- x_{i+1} exists.

If there exist such y_i steps 5-7 are repeated

8. Whenever a distinct option exists for y_2, $i = 2$ is assigned and jump to step 7.
9. Whenever a distinct option exists for x_2, $i = 2$ is assigned and jump to step 6.
10. Whenever a distinct option exists for y_1, $i = 1$ is assigned and jump to step 4.
11. Whenever a distinct option exists for x_1, $i = 1$ is assigned and jump to step 3.
12. Whenever a distinct option exists for t_1, jump to step 2.
13. Stop

Detailed explanations for this pseudocode for Lin-Kernighan algorithm can be found in [28] from page 12-14.

6 Implementation and Data Collection

This section presents the implementation specifics for this thesis as well as the proposed solution for the digital order picking system. In this section is is also discussed about the data retrieval from the SAP system of Bauer Gear Motor to integrate it with the developed solution. The sections of this chapter are as follows:

- Technology used to develop the prototype – An overview of the tools and technologies used for developing the digital picking system.
- Data collection – Overview of how the data was collected and filtered for processing and getting desired results.
- Implementation of TSP heuristics – As discussed in chapter 5, implementation of all 4 TSP heuristics has been presented in detail.

6.1 Technology Used To Develop Prototype

Figure 6.1 shows a general overview of the software architecture used to implement the proposed solution as described in the chapter 5.

6.1.1 Data Acquisition Layer

Data acquisition layer plays a vital role in extracting the data and mapping it into the .csv file which is then accessed from the python to get necessary information for producing the optimal path. In this thesis the developed prototype does not access the SAP system which is the main ERP system for the company as it is a live system and integration of the system with developed prototype can cause potential hazards for the smooth operation of the companies' day to day operations. Hence data is extracted from the SAP system using a small query.

Incoming order numbers which are stored in the database is then filtered and mapped into a .csv file for further execution. Table 6.1 shows a specimen of the .csv file, and the relevant data used in this prototype.

These values are used by the program which is written in Python 3 to provide the picker with the near optimal route.

Bin location is another static .csv file which store the coordinates (x, y) of the bin location situated in the warehouse. This file is again accessed by the Python program to create necessary graphs and distance matrix to perform the necessary calculations. Table 6.2 shows a part of the bin location .csv file.

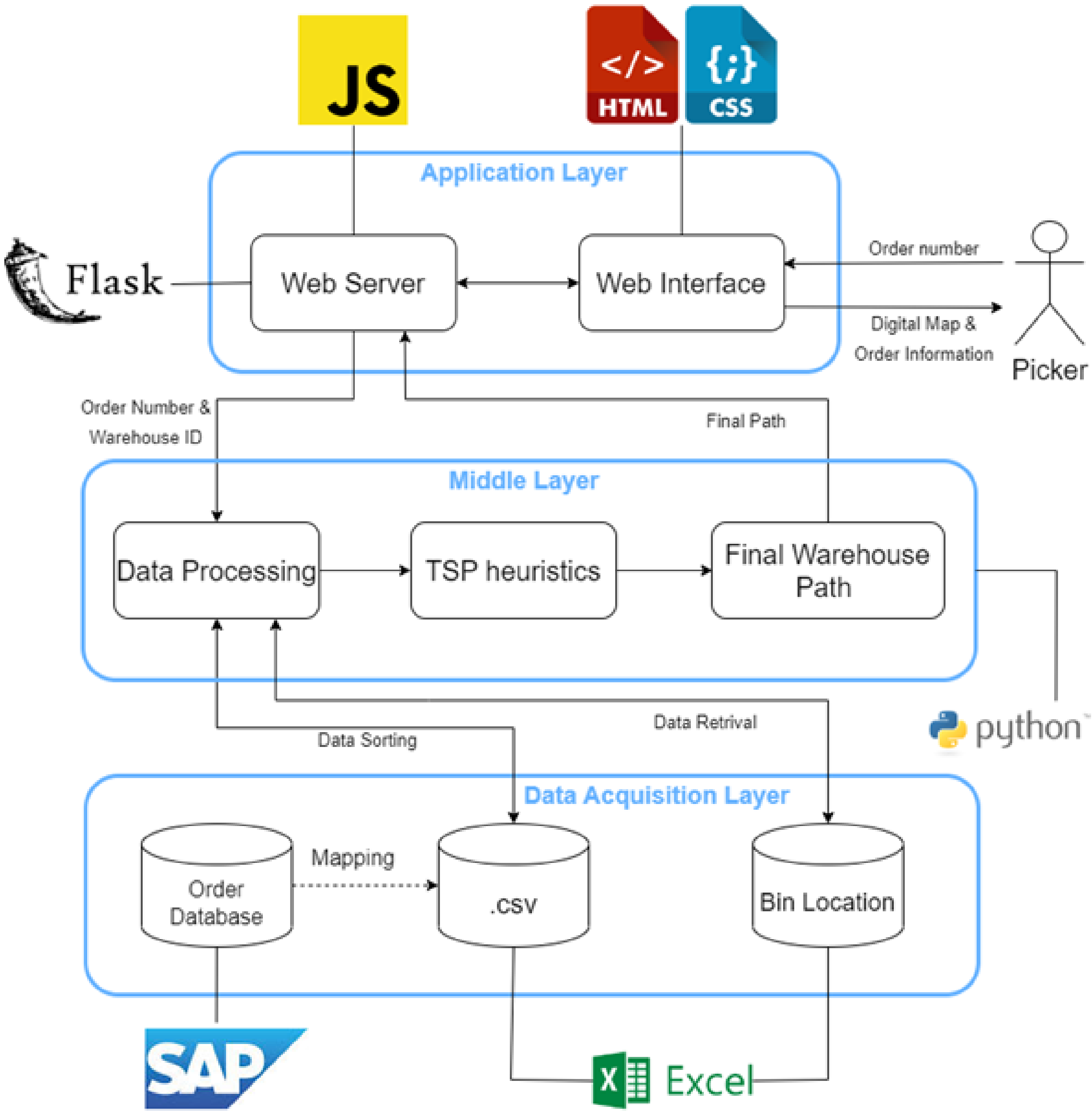


Figure 6.1: Software system architecture.

6.1.2 Middle Layer

Middle layer is developed in Python 3 and is responsible for all the data sorting, generation of graphs, calculation of distance matrix and getting the results from all the 4 TSP heuristics. Detailed information about the implementation of the TSP heuristics is provided in the next section of this chapter.

Middle layer can be divided into 3 main parts as shown in figure 6.1. Data processing, TSP heuristics and final warehouse path. Operation of these 3 parts are as follows:

Sales Document	Sales Document Item	Material	Description	Order Quantity	Plant	Storage Location	BIN Location	Shipping Point	Bauer Mat. Number
2383098	10	30370442	GEARWHEEL BG40-R3-1 (11-1,75) (BF40)	4	2390	10	3I06D02	2393	BAU2503417
2383098	30	30367906	GEAR HOUSING, FOOT BG40-02-A1**	2	2390	10	3J02A01	2393	BAU2503751
2383098	60	30370487	GEARWHEEL BG50-R3-3 (19-2,5) (BF50)	2	2390	10	3I06D07	2393	BAU2506475
2383098	80	30370518	GEARWHEEL BK60-R5-1 (12-3)	5	2390	10	3C03A03	2393	BAU2507455
2383098	90	30368038	GEAR HOUSING BK90-01-A1 P.2C**	2	2390	10	3A11A02	2393	BAU2514834
2383098	100	30370520	GEARWHEEL BK60-R6-1 (63-3)	5	2390	10	3A04A02	2393	BAU2507471
2383098	110	30368612	SYSTEMCOVER D09-B40-10-A2-AL P.2	10	2390	10	3H05B04	2393	BAU2532816
2383098	150	30365474	FAN COWL D09-76-EG-A3 P.1.1	3	2390	10	3G01E05	2393	BAU2578409
2383098	160	30370597	GEARWHEEL BK80-R5-2 (13-5)	1	2390	10	3D05A02	2393	BAU2512653
2383098	170	30366460	OUTPUT SHAFT BS40-36-A3	2	2390	10	3M01B02	2393	BAU2503051
2383098	180	30367933	GEARBOX HOUSING, FOOT BG50-02-A1**	3	2390	10	3J01A02	2393	BAU2506921
2383098	190	30366562	SPACER BK80-70-A4 POS.3	2	2390	10	3B07B03	2393	BAU2512831
2383098	210	30368042	SYSTEMCOVER D13-B50-10-A2 P.1	2	2390	10	3K01A01	2393	BAU2515385
2383098	220	30370109	DISK SPRING 108X149X1,25MM	4	2390	10	3I01L16	2393	BAU2533308
2383098	260	30366469	OUTPUT SHAFT BG40-30-A3	5	2390	10	3I07B05	2393	BAU2503140

Table 6.1: Specimen for order number 2383098.

Bin Location	X_Coordinate	Y_Coordinate
3A01	1	2
3A02	1	3
3B02	1	9
3B01	1	10
3C01	4	2
3C02	4	3
3D02	4	9
3D01	4	10

Table 6.2: Snippet of Bin Location file.

- Data processing: This part of the middle layer is responsible for recording the order number provided by the picker and then access the .csv file as mentioned earlier. This part looks for the perfect match of the order number provided and retrieves the data as shown in Table 6.1. If the order number is not present, then it tells web server to throw an error. Data from the .csv file is then stored in the form of dictionary which contains multiple arrays with specific key value. As soon as this process of data retrieval from the database is completed, another csv file as mentioned in Table 6.2 is accessed. In this process first 4 values of the bin location are matched with the data present in the bin location .csv file and accordingly the X and Y coordinates are stored into another array. This array contains the X and Y coordinates of all the items present in that specific order. This is set of arrays is then passed on to next part which is TSP heuristics.

- TSP heuristic: This part of middle layer is responsible to generate the low cost and shortest path possible to travel through the warehouse with all the pick points mentioned in the order picking list from the .csv file. This module investigates 4 different TSP heuristics as mentioned in chapter 5. Nearest neighbour, 2-opt, Christofide's algorithm, and LKH heuristics are implemented and 4 different results from these 4 different heuristics is generated. Implementation of these 4 TSP heuristics is mentioned in the chapter 7. All the generated results are then passed on the next part of the middle layer, Final Warehouse Path.

- Final Warehouse Path: This part of the middle layer is responsible to generate the warehouse map with consideration of all the shelves and walking area with pre-defined rules for entry for the pickers in the specific aisle. All the four different paths generated from by different TSP heuristics have only the coordinates of the pickup location in the form of an array. In this section entire path is generated by adding all the Steiner nodes with their coordinate to make a complete path for the picker. Cost of all the 4 paths is calculated and the one which is with the shortest path is then sent to web server via Flask. Additional to this the data from the picking list is sorted according to the lowest cost path and stored in the dictionary with all the relevant fields mentioned in Table 6.1. Complete path with pickup points and sorted data with links to the pictures is sent to the web server using post method via Flask.

6.1.3 Application Layer

Application layer is consisting mainly of two main parts which are web interface and web server as shown in Figure 6.1. The design and development of the web interface is developed with the help of Hyper Text Markup Language (HTML) and Cascading Style Sheets (CSS). The layout and positioning of the digital map, relevant data for picking and the images with option to select the warehouse is written in HTML. Designing and colour coding scheme for the web page is done by using CSS.

Web server section is responsible for the smooth working and functionality of the web page. The backend of the webpage which is handled by web server is developed using JavaScript. Code developed in JavaScript is responsible to record the order number and the selected warehouse entered by the picker and forward it the data processing section of the middle layer. Once the complete path has been generated along with the data sorting, it is responsible to get this data from the middle layer and process it to display the digital map and all the relevant picking information related to the items to be picked up. The digital map for traversing the warehouse is made with the help of D3.js [19]. With D3.js an 18 x 20 grid is made which represents the actual layout of the warehouse present in Bauer Gear Motor in Esslingen. All the data which is transferred from middle layer to application layer is stored in JavaScript Object Notation (json) format and accessed by D3.js to make a digital map. All the cells are either assigned as shelving cells, path cells, pick up cells, source cell or navigable cell.

- Source cell is highlighted in red colour and represented as starting and ending point for all the routes.
- Shelving cells represent the location of the cells when all the parts are stored, and this is exact representation of an actual storage in the warehouse.
- Path cells are represented in white colour and represent the path which picker need to take or walk on in order to pick up all the parts.
- Pick up cells represent the location of the items which are in the order list and where the picker need to go in order to pick up the items mentioned in the list.
- Navigable cells are represented in black colour and denote the walking area where picker can walk but is recommended as it will disturb the optimal tour given by the algorithm.

```
<svg>
    <defs>
        <marker
            id="arrow"
            markerUnits="strokeWidth"
            markerWidth="12"
            markerHeight="12"
            viewBox="0 0 12 12"
            refX="6"
            refY="6"
            orient="auto">
            <path d="M2,2 L10,6 L2,10 L6,6 L2,2" style="fill: #f00;">
            </path>
    </marker>
    </defs>
</svg>
```

Listing 6.1: Code for adding arrows for direction on path cells.

Development of the digital map can be studied in detail by accessing the website mentioned in [24].

Path cell are also assisted with arrows which helps picker understand how to navigate through the warehouse more efficiently. Below code is used for marking the cell and the path with arrows for better navigation.

Web interface is the web page which run on the localhost:5000 contains field to choose the warehouse type and to enter the order number. After entering the detail picker gets the detailed map with highlighted path and relevant information with pictures which helps them to complete the task in less time and high precision.

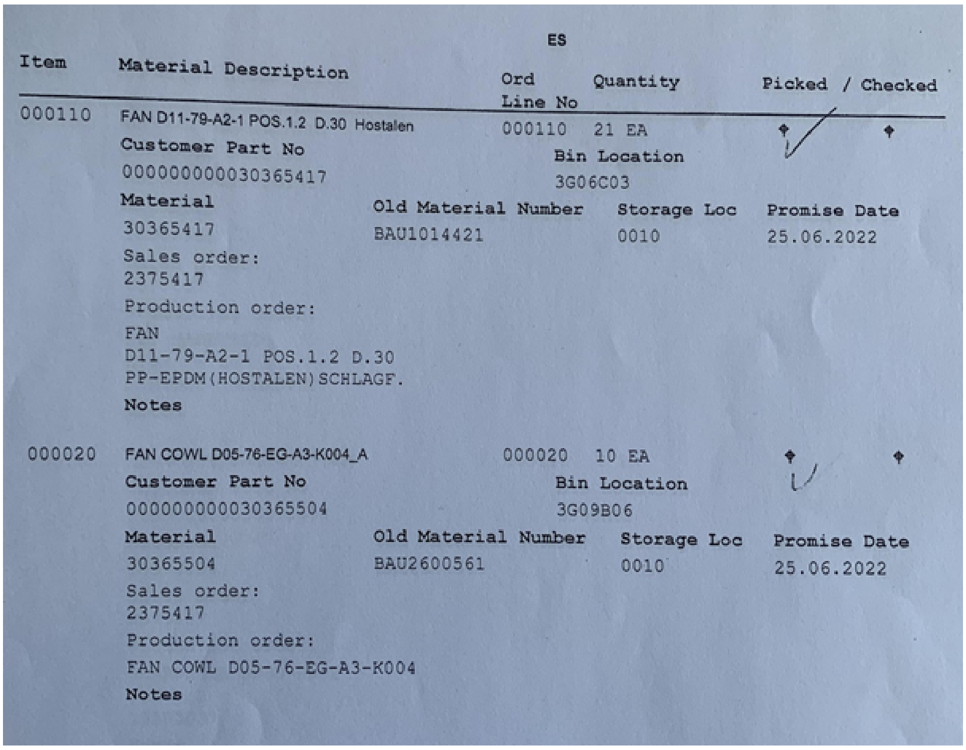
6.2 Data Collection

In conventional method or with respect to ongoing process the order picking is done with help of the paper-based picking system. An example of paper-based picking list is shown in Figure 6.2.

To collect the data for evaluation of the various algorithm, a query in SAP database is executed and all the data is stored in the .csv file as shown in Table 6.1.

To evaluate the performance of the developed prototype against the existing paper-based system in terms of distance and time required to pick the entire order, data is collected by walking with the picker in person and picking the same order with the developed system. Data is recorded in terms of time and distance for both technologies and the results are discussed in chapter 7.2.

To conduct an economic analysis, overall usage in terms of paper, ink, energy usage and man hours are extracted from the company database (spare parts department) and evaluated against the developed prototypes. Results of the economic analysis is discussed in chapter 7.3.



ES

Item | Material Description | Ord Line No | Quantity | Picked / Checked

000110 FAN D11-79-A2-1 POS.1.2 D.30 Hostalen 000110 21 EA
Customer Part No
000000000030365417
Bin Location
3G06C03
Material Old Material Number Storage Loc Promise Date
30365417 BAU1014421 0010 25.06.2022
Sales order:
2375417
Production order:
FAN
D11-79-A2-1 POS.1.2 D.30
PP-EPDM(HOSTALEN)SCHLAGF.
Notes

000020 FAN COWL D05-76-EG-A3-K004_A 000020 10 EA
Customer Part No
000000000030365504
Bin Location
3G09B06
Material Old Material Number Storage Loc Promise Date
30365504 BAU2600561 0010 25.06.2022
Sales order:
2375417
Production order:
FAN COWL D05-76-EG-A3-K004
Notes

Figure 6.2: Paper-based picking list used in Bauer Gear Motor GmbH.

6.3 Implementation of TSP Heuristics

This section describes about all the 4 TSP heuristics (nearest neighbour, 2-opt, Christofide's, and LKH algorithm) implemented in this thesis and how they perform for the same set of order is also shown. A single order is taken to represent the different path produced by these different algorithms and cost respective to it. This work does not consider greedy algorithm as mentioned earlier as it does not have a fixed starting point, and greedy algorithm chooses the starting point at random.

A random order is taken from the database and is shown in Table 6.3. This order is given as an input to all 4 algorithms and results are shown.

Once the data is retrieved from the database with the coordinates for the pick-up points, a graph is created using the NetworkX Library [27]. NetowrkX library can create, load, and store complex graphs which can be used further for various purposes. Once the graph is created, distance matrix is generated using nx.shortest-path-length to get the shortest lengths from one node to all other nodes. This is repeated for all the nodes or the pick-up points. Once this is created, distance matrix is created and stored in a function. Distance matrix for example given in Table 6.3 is shown in Table 6.4.

Following images represent the actual implementation of all the 4 TSP heuristics mentioned earlier with their results for the same order mentioned in Table 6.3. Snippets of python code is presented with a detailed tour of given by each algorithm for better understanding of the results produced by

Order Number	Material Number	Description	Qty	Bin Location	Bauer Number	X Coordinate	Y Coordinate
2433376	30367937	GEARBOX HOUSING, FOOT BG60-02-A1**	2	3A02A01	BAU2507684	1	3
2433376	30368021	GEARBOX HOUSING, FOOT BG70-02-A1 P.2B**	2	3A15A01	BAU2513722	1	16
2433376	30366528	OUTPUT SHAFT BG70-30-A3	1	3B02B03	BAU2508346	1	9
2433376	30366523	OUTPUT SHAFT BG60-30-A3	2	3B04B01	BAU2507676	1	7
2433376	30367942	HOUSING COVER BG70-60-A2	2	3D07A01	BAU2508362	4	4
2433376	30367948	SYSTEMCOVER D11-B60-10-A2 P.1**	1	3G06A03	BAU2508681	11	7
2433376	30367991	SYSTEMCOVER D11-B70-10-A2 P.1(BF80)	2	3G07A01	BAU2511151	11	8
2433376	30366469	OUTPUT SHAFT BG40-30-A3	1	3I07B05	BAU2503140	14	8
2433376	30367906	GEARBOX HOUSING, FOOT BG40-02-A1**	1	3J02A01	BAU2503751	16	9

Table 6.3: Picklist 2433376

	Source (15,0)	**3A02A01 (1,3)**	**3A15A01 (1,16)**	**3B04B01 (1,7)**	**3B02B03 (1,9)**	**3D07A01 (4,4)**	**3G06A03 (11,7)**	**3G07A01 (11,8)**	**3I07B05 (14,8)**	**3J02A01 (16,9)**
Source (15,0)	0	17	30	21	23	15	11	12	9	10
3A02A01 (1,3)	17	0	13	4	6	8	18	19	22	25
3A15A01 (1,16)	30	13	0	9	7	15	19	18	21	22
3B04B01 (1,7)	21	4	9	0	2	12	18	17	20	21
3B02B03 (1,9)	23	6	7	2	0	12	16	15	18	19
3D07A01 (4,4)	15	8	15	12	12	0	16	17	20	21
3G06A03 (11,7)	11	18	19	18	16	16	0	1	10	11
3G07A01 (11,8)	12	19	18	17	15	17	1	0	9	10
3I07B05 (14,8)	9	22	21	20	18	20	10	9	0	7
3J02A01 (16,9)	10	25	22	21	19	21	11	10	7	0

Table 6.4: Distance matrix (Order number 2433376).

each algorithm. Each algorithm is implemented as a function and returns the final tour with an array of coordinated of all the pick-up points. These results are then passed on to another module which generates the entire tour by adding all the Steiner nodes to get a complete path in the warehouse.

Nearest Neighbour Algorithm

As explained in chapter xyz, nearest neighbour algorithm is implemented in Python and shown in Figure 6.3.

```python
def NN(graph, pick_points, source):

    points = [source] + pick_points
    distance = get_distance_matrix(graph, points)
    G = create_graph(points, distance)
    current_node = source
    path = [current_node]
    n = G.number_of_nodes()

    for _ in range(n - 1):
        next_node = None
        min_dist = 1000000
        for i in G.nodes:
            if i!=current_node:
                if G.adj[current_node][i][0]['weight'] < min_dist and i not in path:
                    array1 = []
                    array1.clear
                    min_dist = G.adj[current_node][i][0]['weight']
                    array1.append(i)
                    xyz = array1[-1]
                    next_node = xyz
        assert next_node is not None
        path.append(next_node)
        current_node = next_node
    path = path + [source]
    print(path)
    min_cost = 0
    for a in range (0, (len(path)-2)):
        ccost = G.adj[path[a]][path[a+1]][0]['weight']
        min_cost = min_cost + ccost
    return path
```

Figure 6.3: Implementation of Nearest Neighbour algorithm.

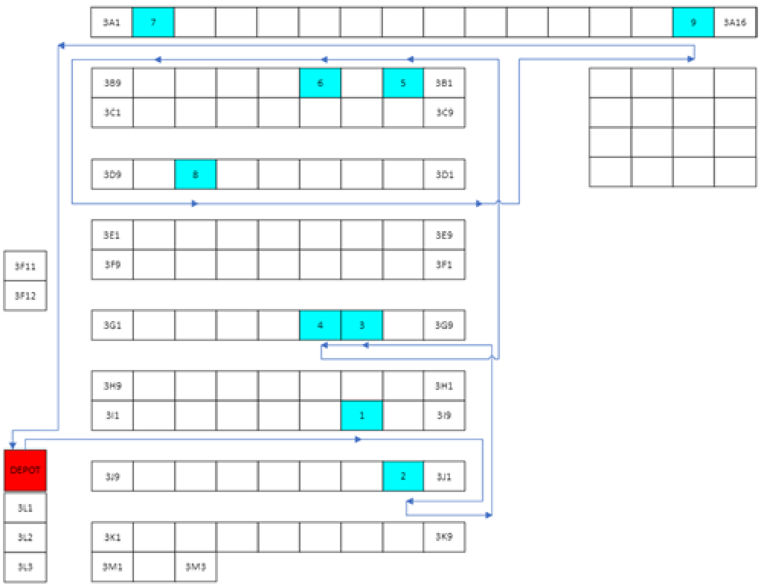


Figure 6.4: Nearest Neighbour schematic representation. Path Cost 112.

2-Opt Algorithm

As explained in chapter xyz, 2-opt algorithm is implemented in Python and shown in Figure 6.5.

```python
def two_opt(graph, pick_points, source):
    # create graph G
    points = [source] + pick_points
    distance = get_distance_matrix(graph, points)
    G = create_graph(points, distance)
    current_node = source
    path = [current_node]
    n = G.number_of_nodes()

    tour = list(G.nodes)
    tour = tour + [source]
    improved = True
    cost = 10000
    improved_path = None
    while improved:
    #for i in range(0,150):
        improved = False
        for i in range(G.number_of_nodes()):
            for j in range(i+1,G.number_of_nodes()):
                    # two current edges from tour
                    cur_length = G.adj[tour[i]][tour[i+1]][0]['weight'] + G.adj[tour[j]][tour[(j+1)%n]][0]['weight']
                    # two 'new' edges for the tour
                    new_length = G.adj[tour[i]][tour[j]][0]['weight'] + G.adj[tour[i+1]][tour[(j+1)%n]][0]['weight']
                    # update the tour, if improved
                    improved_path = None
                    if new_length < cur_length:
                        tour[i+1:j+1] = tour[i+1:j+1][::-1]
                        min_cost= 0
                        for a in range (0, (len(tour)-2)):
                            ccost = G.adj[tour[a]][tour[a+1]][0]['weight']
                            min_cost = min_cost + ccost
                        if min_cost <= cost:
                            improved_path = tour
                            cost = min_cost
                            improved = True
                            return improved_path
```

Figure 6.5: Implementation of 2-Opt algorithm.

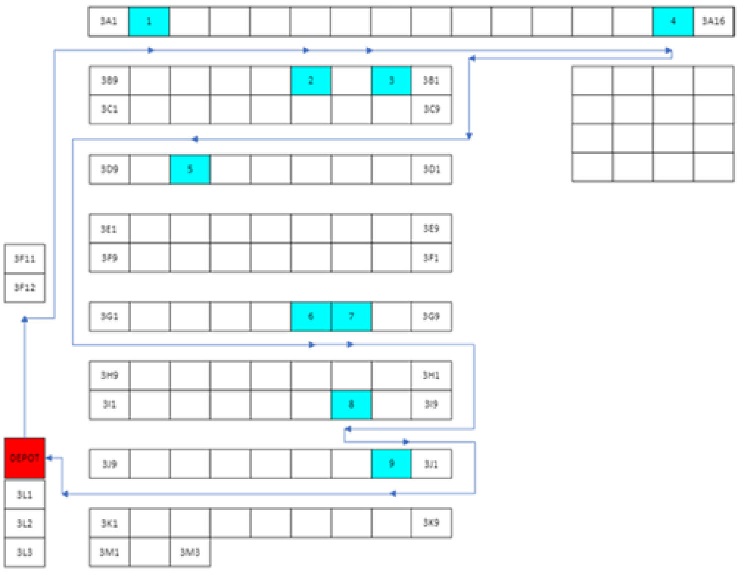


Figure 6.6: 2-opt algorithm schematic representation. Path Cost 102.

Christofide's Algorithm

As explained in chapter xyz, Christofide's algorithm is implemented in Python and shown in Figure 6.7.

```python
def christofides(graph, pick_points, source):

    # graph G
    points = [source] + pick_points
    distance = get_distance_matrix(graph, points)
    G = create_graph(points, distance)

    # minimum spanning tree of G
    T = nx.minimum_spanning_tree(G)

    # nodes with odd degree in T
    odd_degree_nodes = get_nodes_with_odd_degree(T)

    # subgraph S of odd degree nodes in T
    S = G.subgraph(nodes=odd_degree_nodes)

    # perform min-weight perfect matching of the nodes in S
    min_weight_perfect_matching(T, S)

    # euler circuit
    euler_tour = []
    get_euler_tour(T, source, euler_tour)

    # hamiltonian circuit
    final_tour = get_hamiltonian_circuit(euler_tour, T.number_of_nodes())
    min_cost = 0
    for a in range (0, (len(final_tour)-2)):
        ccost = G.adj[final_tour[a]][final_tour[a+1]][0]['weight']
        min_cost = min_cost + ccost
    return final_tour
```

Figure 6.7: Implementation of Christofide's algorithm.

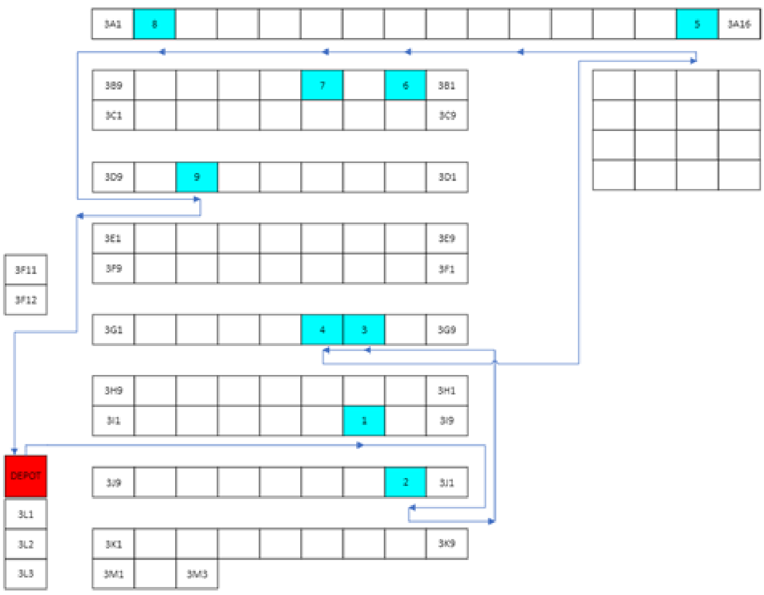


Figure 6.8: Christofide's algorithm schematic representation. Path Cost 92.

Lin-Kernighan Heuristics Algorithm

As explained in chapter xyz, LKH algorithm is implemented in Python and shown in Figure 6.9. Implementation of Lin-Kernighan heuristics is taken directly from [44]. Detailed explanation of the algorithm and implementation can be referred by accessing [44].

```
def LKH(graph, pick_points, source):
    points = [source] + pick_points
    distance = new_distance_matrix(graph, points)
    TSP.setEdges(distance)
    # Make an instance with all nodes
    lk = KOpt(range(len(distance)))
    path, cost = lk.optimise()
    lkh_path = [points[i] for i in path] + [source]
    return lkh_path
```

Figure 6.9: Implementation of LKH algorithm.

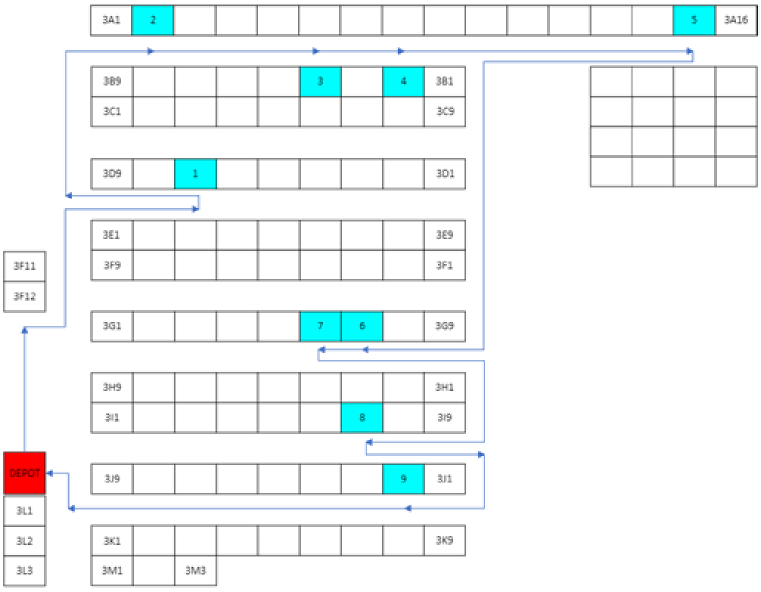


Figure 6.10: LKH algorithm schematic representation. Path Cost 92.

7 Result And Analysis

This chapter gives an overview of the end result of the final prototype which has been developed for digital order picking system for Bauer Gear Motor GmbH, Esslingen warehouse. This chapter is further divided into two sections. Data Analysis and Economic Analysis. Data analysis section describes about the performance of the TSP heuristics used in this thesis and results provided by each algorithm for 50 odd orders. Economic analysis describes and focuses on the savings obtained by using the digital system over an existing paper-based system. Various factors are taken into consideration like paper and ink usage, energy consumption by devices, etc. Data analysis of different heuristics is carried out using real life orders from the spare-parts delivery department and economic analysis is carried out by extracting the real-life data from the company to showcase actual savings in real-life scenario.

7.1 Results

The developed prototype works on a web application and is hosted locally on the Windows 10 machine. As discussed earlier,. web interface is developed using JavaScript, HTML, and CSS. Web page can be accessed by the URL *https://localhost:5000* to visit the web interface after running the Flask web server in the python file app.py. Figure **??** displays the web server's home page.

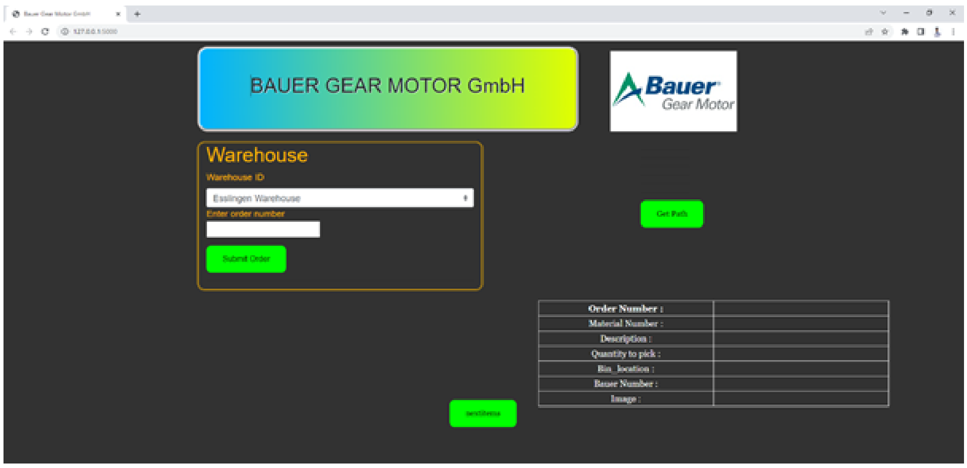


Figure 7.1: Home page for digital order picking.

After accessing the home page, picker selects the warehouse ID (currently limited to only Esslingen) and enters the order number in the field present. After entering the order number,. picker presses the submit button. After this step,. warehouse ID and Order number are sent from the web server to backend python file to process the order. Once this step is complete. picker presses the "Get

Path" button to get the shortest possible path for the given order. After this step, web page displays the shortest routes with the map and path marked with arrows as shown in Figure 7.2. Source and destination cell is highlighted in red colour. Pick up nodes/points are highlighted in blue colour and the current position or current pick-up node is highlighted in yellow colour for better navigation through the warehouse. Entire path is marked with white and red arrows for better clarity and to avoid any confusion. In addition to these all the relevant details and the picture of the item to be picked of the order are displayed on the right-hand side of the map to avoid any confusion and decrease picking error as shown in Figure 7.2.

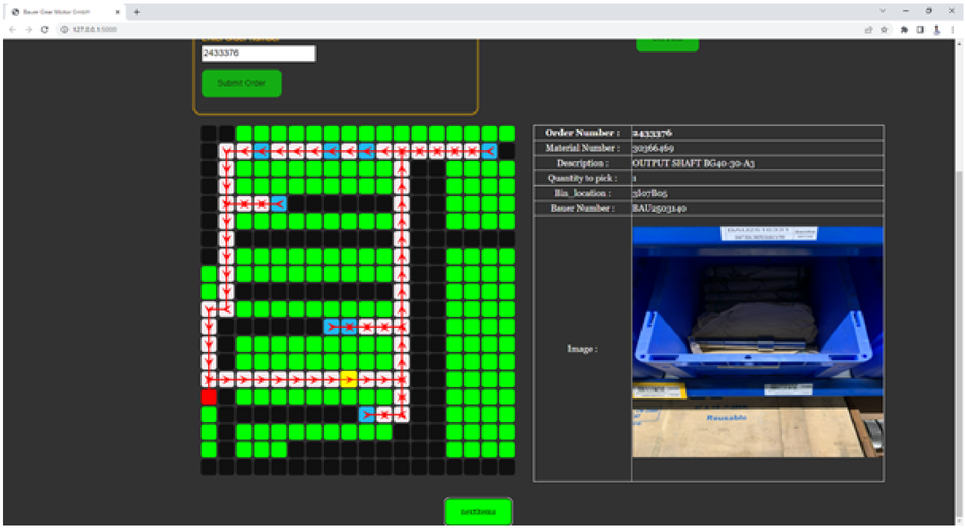


Figure 7.2: Path and details for order *2433376*.

Once the picker has picked up the item from the bin, picker presses the next item button to get the next location and details to pick. This results in an optimised picking process with minimal picking errors.

7.2 Data Analysis

This section describes the performance analysis of the 4 TSP heuristics used in this thesis and their outcomes for all 50 random orders tested on this prototype. For all orders tested on this device. distance of the route provided by each heuristic is recorded as well as the computation time of each heuristic. All 50 orders were tested on the windows 10 PC. HP ZBook 14u G5 with Intel Core i7-8550U CPU @ 1.80GHz 1.99 GHz processor. 16GB RAM and 64-bit operating system. Detailed values for all orders tested on the developed prototype is mentioned in appendix A. Table 7.1 shows the average distance given by each algorithm used and average computation time by each heuristic.

From Table 7.1, Figure 7.3 and 7.4 Christofide's algorithm gives the shortest path on an average for all the orders tested. Even though computation time for Christofide's algorithm is a bit higher than Nearest-neighbour algorithm and 2-opt algorithm but all the computation time is in milliseconds, hence a delay of a few milliseconds is irrelevant for the output to a human.

Algorithm/Heuristics	Average Cost	Average Computing Time
Nearest Neighbour Algorithm	99.78 m	19 ms
2-Opt Algorithm	102.74 m	18 ms
Christofide's Algorithm	95.54 m	21 ms
LKH Algorithm	103.06	58 ms

Table 7.1: Average cost and computation time.

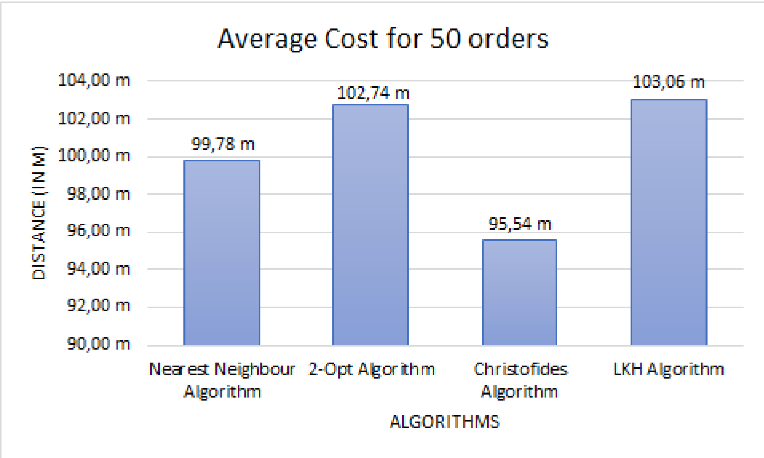


Figure 7.3: Average cost by algorithms.

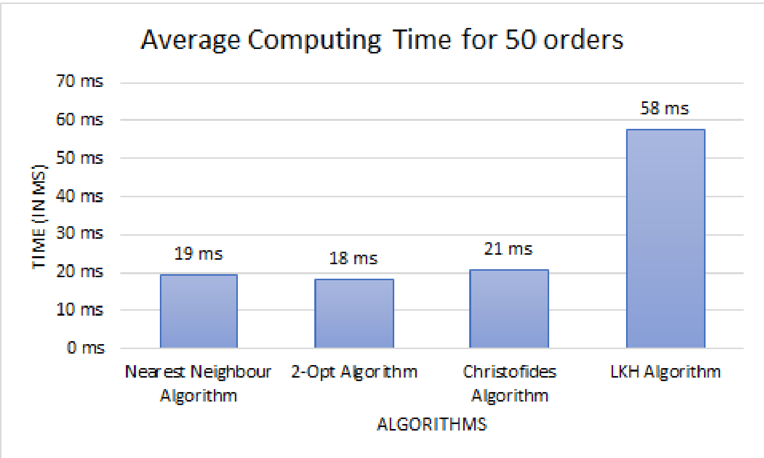


Figure 7.4: Average computation time by algorithms.

Appendix A also shows that there is significant reduction in travelling distance for a picker compared to existing technique of S-shaped which is been used to perform the picking activity. Figure 7.3 and 7.4 gives us clear result that using Christofide's algorithm to find the near optimal path is best choice for the give warehouse structure in Bauer Gear Motors GmbH. Hence further study has been carried out to compare the travelling distance between existing paper-based system and Christofide's algorithm outputs. Distance travelled by a picker with paper-based system has been carried out manually by travelling with the picker in the warehouse and recording the route taken by the picker.

Algorithm/Heuristics	Percentage
Nearest Neighbour Algorithm	10 %
2-Opt Algorithm	12 %
Christofide's Algorithm	54 %
LKH Algorithm	24 %

Table 7.2: Distribution of algorithms in terms of shortest path.

This data is then compared with the distance and route given by Christofide's algorithm. Figure 7.5 shows the difference in travelling distance when paper-based system is used and when the developed prototype is used. From this analysis average savings in terms of distance travelled by the pickers for all 50 orders is 17 % when Christofide's algorithm is used against existing S-shape technique used for picking process.

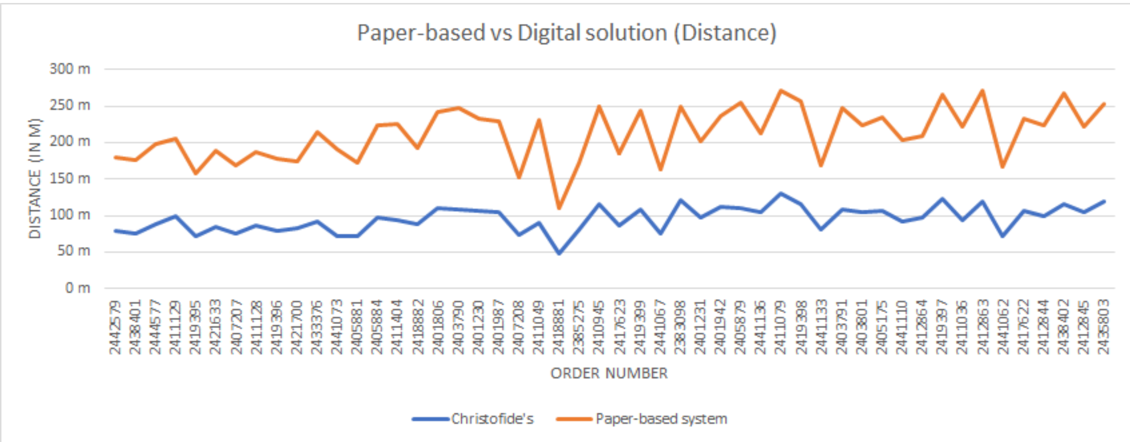


Figure 7.5: Comparison of distance between paper based and Christofide's route.

Furthermore, it was also recorded that even though Christofide's algorithm has the lowest overall average value for the distance it did not always gives the lowest path compared to the other 3 heuristics (Nearest neighbour, 2-opt, Lin–Kernighan heuristic). Table 7.2 shows the percentage distribution of all the 4 TSP heuristics used for providing the shortest paths for 50 orders tested.

From Table 7.2 it is clear that Christofide's algorithm gives the shortest path for only 27 out of 50 orders following the Lin—Kernighan heuristic by giving the shortest path for 12 orders out of 50. In other cases. Nearest neighbour and 2-opt algorithm provides better route than other two algorithms. Hence a small feature is added in the developed prototype to compare cost of all these algorithms and return the route with the smallest distance. After implementing this feature in the prototype instead of just using the routes provided by Christofide's algorithm. average reduction in distance travelled by the picker increases from 17 % to 20 %. Figure 7.6 shows the difference in distance between the shortest path and existing paper-based system. Detailed analysis is shown in appendix A.

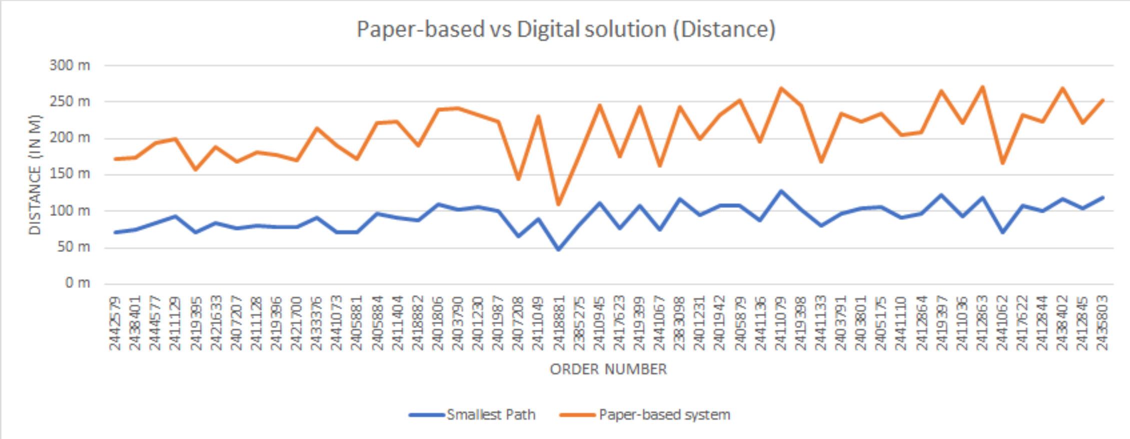


Figure 7.6: Comparison of distance between paper-based and digital solution.

7.3 Economic Analysis

This section describes the economic benefits of using the developed digital system over the existing paper-based system in terms of profitability and reduction in carbon footprints. In today's world all process carried out in logistics sectors are turning towards digitalisation to save the cost and increase efficiency. Also., an important motive behind adopting digital process over paper-based process is to reduce carbon footprints by eliminating the paper usage in the whole process. In this section a detailed analysis has been carried out on economic savings taking several factors into considerations like usage of paper, cost of ink and paper, power usage of printer to print,. man hours, and power usage of digital system to run over a year. Data to calculate the number of papers that were printed in the year 2022 was taken out from the spare parts department as the main aim of this thesis was to focus on this department. Table 7.3 shows the relevant data for economic analysis in terms of all the parameters which were considered.

Month	No. of orders	No of items	No. of pages printed	Money spent on pages	Money spent on printing (Toner)	Hours spent on printing	Money spent on energy usage by a printer	Cost of worker for printing pages and sorting	Cost for charging a laptop
January	1413	3354	2384	11.92 €	71.52 €	3.24 h	1.04 €	135.00 €	1.50 €
February	1390	2539	1965	9.83 €	58.95 €	2.67 h	0.86 €	135.00 €	1.50 €
March	1667	3290	2479	12.40 €	74.37 €	3.37 h	1.08 €	135.00 €	1.50 €
April	1344	2916	2130	10.65 €	63.90 €	2.90 h	0.93 €	135.00 €	1.50 €
May	1474	2810	2142	10.71 €	64.26 €	2.92 h	0.93 €	135.00 €	1.50 €
June	1262	2427	1845	9.23 €	55.35 €	2.51 h	0.80 €	135.00 €	1.50 €
July	1131	2304	1718	8.59 €	51.54 €	2.34 h	0.75 €	135.00 €	1.50 €
August	1139	2508	1824	9.12 €	54.72 €	2.48 h	0.79 €	135.00 €	1.50 €
September	1117	2475	1796	8.98 €	53.88 €	2.44 h	0.78 €	135.00 €	1.50 €
October	1327	2736	2032	10.16 €	60.96 €	2.77 h	0.89 €	135.00 €	1.50 €
November	1327	2736	2032	10.16 €	60.96 €	2.77 h	0.89 €	135.00 €	1.50 €
December	1327	2736	2032	10.16 €	60.96 €	2.77 h	0.89 €	135.00 €	1.50 €
Total	**15918**	**32831**	**24379**	**121.90 €**	**731.37 €**	**33.183 h**	**10.62 €**	**1.620.00 €**	**18.00 €**

Table 7.3: Data for economic analysis.

Cost of one page is 0.01 € with cost of printing one page is 0.03 € (cost of ink/toner used to print one page). These numbers are multiplied with the total number of pages printed per month to get total expenditure of pages and ink used in a particular month. This data was collected in the last week of September hence for remaining months of October. November and December is considered the average value calculated from figures obtained from January to September. To calculate time spent to print one page,. catalogue of printer used in the warehouse was accessed [54]. This data was then multiplied with number of pages printed in that month. Data for power usage to print one paper is also taken from [54]. In economic analysis cost of man hours has been considered as the printing process takes place in the morning and all the pages are printed at once. Hence approximately 5 man hours per month is spent on sorting the orders and staking up according to region. The assumed hourly rate of a picker is 27 € which gives us 135 €/month cost of picker just for sorting.

Digital solutions also need initial investment and need power to be operational in real life scenario. Hence initial cost of an average laptop is considered as 300 € and in total 4 pickers work in spare parts department at a time. An initial cost of 1,200 € is considered and life period of 5 years. After 5 years all the laptops need to be replaced with new ones. Monthly expenditure to charge a laptop is approximately around 0.38 € [22]. As a result, it comes to 18 € to charge all 4 laptops per year. Figure 7.7 shows us the trend of expenditure over the next 10 years considering the average number of orders remain same for upcoming years. If number of orders are about to increase, then more savings can be expected from a digital system used for order picking process.

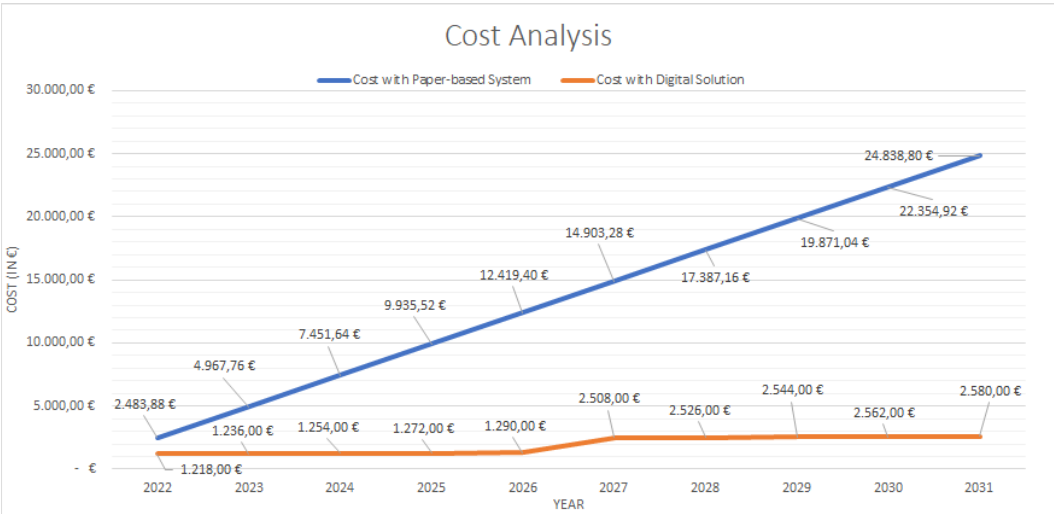


Figure 7.7: Trend of expenditure over the next 10 years.

From Figure 7.7, it is calculated that there can be almost 83 % of saving by year 2024 and 88 % savings by year 2026. It is clear that the company can save money on printing and sorting process which plays a key role in paper-based picking system. Companies today are interested in transforming the manual or paper-based systems into digital and automated process to not only save money and increase efficiency, but companies today are also interested in reducing the carbon footprints to save climate change. To manufacture a single piece of paper approximately 5 g of CO2 is released and to print a single sheet of paper 1 g of CO2 is released. In total if a single sheet is printed, approximately 6 g of CO2 is released [32].

From [12] a laptops life cycle is estimated to be 4 years of use and over 4 years of use, an average laptop produces 61.5 kg of CO2. This means per month usage of laptop produces 1.2 kg of CO2. Table 7.4 shows the overall CO2 emissions for the year 2022.

Month	No. of orders	No. of pages printed	CO2 per month by paper-based systems (grams)	CO2 per month by digital systems (grams)
January	1413	2384	14304 grams	1200 grams
February	1390	1965	11790 grams	1200 grams
March	1667	2479	14874 grams	1200 grams
April	1344	2130	12780 grams	1200 grams
May	1474	2142	12852 grams	1200 grams
June	1262	1845	11070 grams	1200 grams
July	1131	1718	10308 grams	1200 grams
August	1139	1824	10944 grams	1200 grams
September	1117	1796	10776 grams	1200 grams
October	1327	2032	12192 grams	1200 grams
November	1327	2032	12192 grams	1200 grams
December	1327	2032	12192 grams	1200 grams

Table 7.4: CO2 emissions for the year 2022 for paper-based and digital system

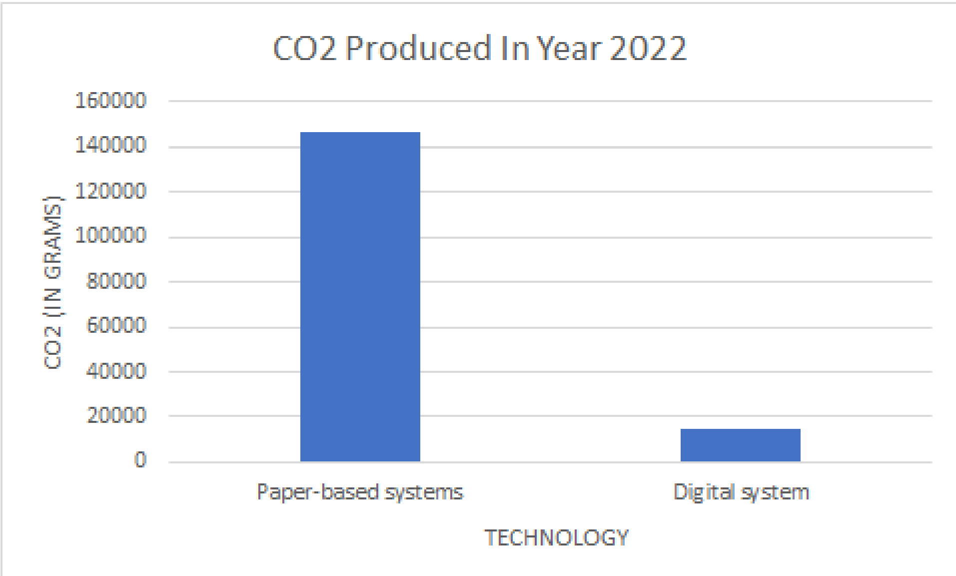


Figure 7.8: CO2 produced by different technologies.

From Figure 7.8, existing paper-based system produces 146.27 kg of CO2 in the year 2022 while digital system produces just 14.4 kg of CO2 in an entire year. By replacing the existing pick by paper with the developed prototype it will result in 90 % reduction in CO2 emission. For better understanding there is a comparison between the CO2 produced per year by pick by paper system and CO2 emitted by a car to travel 1 km. As per [2] in 2018 average CO2 emissions from new passenger cars registered in the European Union (EU) emits 120.4 grams of CO2 per km. Taking this data as a base, CO2 emitted by pick by paper system in a year is equivalent to 1,214 Kilometers (kms) driving on a passenger car.

Real Life Use-Case

A real-life use-case is taken for economic analysis to conclude the analysis of this thesis. A case of an important customer of Bauer Gear Motor GmbH is considered and orders spare parts in huge quantity over the course on a year. It is calculated that there will be a significant rise in spare parts orders to be shipped in the coming years. A timed run was made with the picker for picking the parts for this customer and it was found out that with paper-based system average time to pick one part is 53.57 seconds and with digital system it comes down to 32.93 seconds. Expected increase in coming years and average time is take into consideration for this analysis. Table 7.5 shows the detailed data of the use-case considered for economic analysis.

Year	**2022**	**2023**	**2024**	**2025**
Expected Growth		33 %	25 %	25 %
Shipped volume (No. of Parts)	65376			
Expected Volume (No. of Parts)		87168	108960	136200
Time spent to pick with paper-based system (seconds)	3502285,71 seconds	4669714,29 seconds	5837142,86 seconds	7296428,57 seconds
Time spent to pick with paper-based system (hours)	972,86 hrs	1297,14 hrs	1621,43 hrs	2026,79 hrs
Time spent to pick with digital system (seconds)	2152738,29 seconds	2870317,71 seconds	3587897,14 seconds	4484871,43 seconds
Time spent to pick with digital system (hours)	597,98 hrs	797,31 hrs	996,64 hrs	1245,80 hrs
Money spent on picker with paper-based system	26.267,14 €	35.022,86 €	43.778,57 €	54.723,21 €
Money spent on picker with Digital system	16.145,54 €	21.527,38 €	26.909,23 €	33.636,54 €
No.of Pickers needed with paper based system	0,7	0,9	1,2	1,4
No.of Pickers needed with digital system	0,4	0,6	0,7	0,9
Savings	**10.121,61 €**	**13.495,47 €**	**16.869,34 €**	**21.086,68 €**

Table 7.5: Data for Use-Case.

From Table 7.5, there is significant savings for the orders considered for an important customer. The developed system not only saves money spent on pickers to do the job but in couple of years instead in 2 pickers only 1 picker is needed to do the job even with the increased number in orders. Hence the other person can be used in doing another job when demand is more, and workforce is less. Analysis carried out in this use case depends on the average time recorded by travelling with picker picking the same order with paper list and again same order with digital solution. Only few orders were tested with both techniques hence the outcome of this analysis can differ if more orders are tested. But for the time-being this data gives satisfactory results and thus pickers can pick more orders in same amount of time.

8 Conclusion

In this thesis a digital system or pick by device technology have been investigated and implemented to increase the efficiency, reduce carbon footprints and to increase profit for order picking process focused on Bauer Gear Motor GmbH, Esslingen warehouse. Classical TSP and its modifications/heuristics have been investigated and four different TSP heuristics which were suitable for metric spaces were implemented. In conclusion out of the four different heuristics implemented, Christofide’s algorithm performs best for warehouse dimensions of 18 x 20 both in terms of cost and computation time. Though the computation time for all the heuristics were in milliseconds which does not causes any delay in carrying out the day-to-day activities. Hence it can be said that Christofide’s algorithm suits best for the given warehouse, but results can differ if warehouse design is changed, and number of pickup points are increased to a significant level.

In addition, the developed digital solution for order picking process overcomes the limitations of other technologies of pick by voice and by pick light system by giving the picker more work autonomy by not wearing any gadgets on the body which causes discomfort in carrying out the job for long hours. By using this prototype pickers are more aware of their surrounding and safety is taken into consideration while carrying out this job. It was also recorded that by using the digital system for order picking process, there was 17 % reduction in overall distance when Christofide’s algorithm is used and 20 % reduction when the smallest route is used out of the four algorithms and not limiting only to Christofide’s. From a small case study investigated in this thesis, it can be said that workforce required to do this job can be reduced in coming years and jobs done per day can be significantly increased.

Overall, the proposed solution in this thesis work increases job efficiency, reduces carbon footprints by eliminating the use of paper, ink, and energy required to print these papers and reduces picking errors by referring to visual aids provided to the picker. Appendix B can be referred to know more about the feedback from prickers about the existing technique and the proposed solution in this thesis. By replacing pick by paper with pick by device company can reduce its carbon footprints by 90 % compared to its existing carbon footprint.

8.1 Limitations Of Work

Developed prototype works well with the investigated warehouse and the process of order picking. There are few limitations to this work as the constraints like weight of the item to be picked up is not considered and kept as a future scope where the orders containing heavy items (weighing more than 50 kg) should be split up into two different orders to carry out the picking process by normal cart and for heavy items with forklift.

Current system is not integrated with the live SAP system used by the company where everyday orders are stored. An extract from the SAP system is made to store the orders for spare parts department into a .csv file which is then accessed by the developed software. Another limitation to this work is to investigate deeper into these algorithms and how do they perform under different warehouse and constraints to give near optimum results. From data analysis it was clear that only 54 % of time Christofide's algorithm gave the shortest route. More research needs to be carried out and tested with a greater number of orders to find the best algorithm which provides the shortest path.

Database for visual aid is created separately and is not available in the SAP system. This needs to be integrated further for the whole system to run as one single solution. Another major limitation is the manual work of changing the coordinates of the bin location if the bin locations are changed in an actual warehouse. If the location is changed in real life but not updated in the backend file, then wrong results will be produced and hence will affect the overall efficiency of the order picking process.

Another small limitation of the proposed solution is handling of the digital screen attached to cart as it can be easily damaged and needs to be replaced. Picker needs to be more careful while handling heavy products and using the digital system.

8.2 Future Directions

The prototype for our work currently functions quite effectively, but in this section, there are some suggestions and improvements that can be made in the design as well as other crucial areas for the successful deployment and operation of this digital system for order picking. These improvements include the following.

- Integrate the develop system with existing SAP system for the product to be used as a whole package.
- Orders containing heavy and light items can be separated based on weight and hence each picker can go with a cart and a forklift respectively.
- Combine the existing solution with batch ordering process [1]. Combining the two technologies or approaches can optimise the order picking process even more as the picker does not have to go into the warehouse for every order, it can be combined based on the zones and different pickers can pick items for different customers in one run based on different zones.
- The proposed solution can be integrated with portable printers to save the time which is spent on making handwritten labels for rechecking process before shipping. In addition to this, handheld scanners can be connected to the developed system for auto update of inventory database.
- More research can be done by taking the developed prototype as the base and if this process can be optimised by AI solvers to get better results.

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Acronyms

.csv Comma Separated File. 32

AI Artificial Intelligence. 8

AR Augmented Reality. 1

AS/RS Automated Storage and Retrieval Systems. 14

ASRV Automated Storage Retrieval Vehicles. 1

ATSP Asymmetric Travelling Salesman Problem. 20

CO2 Carbon dioxide. 5

CPS Cyber-Physical Systems. 6

CSS Cascading Style Sheets. 44

ERP Enterprise Resource Planning. 31

HF Human Characteristics. 14

HTML Hyper Text Markup Language. 44

IIoT Industrial Internet of Things. 7

IoT Internet of Things. 7

json JavaScript Object Notation. 44

kms Kilometers. 58

LKH Lin–Kernighan Heuristic. vii

MST Minimum Spanning Tree. 37

NACE European Classification of Economic Activities. vi

NP-hard non-deterministic polynomial-time hardness. 4

OPSs Order Picking System. 14

PbL Pick-by-Light. 23

PbP Pick-by-Paper. 23

PbT Pick-by-Terminal. 24

PbV Pick-by-Voice. 24

PTL Pick to Light. 1

PTS Partial Tour Graph. 26

RFID Radio Frequency Identification. 1

SA Situation Awareness. 23

SAP Systems Applications and Products. 31

SCADA Supervisory Control and Data Acquisition. 7

STSP Steiner Traveling Salesman Problem. 2

TSP Travelling Salesman Problem. ii

VRP Vehicle Routing Problem. 22

WMS Warehouse Management Systems. 1

A Appendix A

Order number	No. of Pick-up points	Cost (length of the route)				Time to compute				Cost with paper list	Reduction in distance with Christofide's Algorithm (%)	Reduction in distance with smallest path obtained (%)	Smallest route by
		NN	2-opt	Christofides	LKH	NN	2-opt	Christofides	LKH				
2442579	6	79 m	73 m	79 m	71 m	6 ms	5 ms	8 ms	8 ms	100 m	21%	29%	LKH
2438401	7	74 m	74 m	76 m	74 m	8 ms	5 ms	10 ms	8 ms	100 m	24%	26%	LKH
2444577	7	98 m	92 m	88 m	84 m	8 ms	6 ms	10 ms	10 ms	110 m	20%	24%	LKH
2411129	8	107 m	97 m	99 m	93 m	17 ms	6 ms	10 ms	17 ms	106 m	7%	12%	LKH
2419395	8	82 m	78 m	72 m	79 m	4 ms	4 ms	4 ms	11 ms	85 m	15%	15%	Christofide's
2421633	8	86 m	84 m	84 m	89 m	5 ms	6 ms	5 ms	12 ms	105 m	20%	20%	Christofide's
2407207	9	76 m	80 m	76 m	78 m	8 ms	7 ms	8 ms	17 ms	92 m	17%	17%	Christofide's
2411128	9	89 m	81 m	87 m	82 m	10 ms	5 ms	5 ms	14 ms	100 m	13%	19%	2-opt
2419396	9	81 m	85 m	79 m	80 m	10 ms	7 ms	13 ms	14 ms	99 m	20%	20%	Christofide's
2421700	9	79 m	79 m	83 m	80 m	9 ms	7 ms	11 ms	13 ms	91 m	9%	13%	2-opt
2433376	9	112 m	102 m	92 m	92 m	9 ms	8 ms	11 ms	18 ms	122 m	25%	25%	Christofide's
2441073	9	77 m	81 m	71 m	84 m	8 ms	9 ms	6 ms	21 ms	119 m	40%	40%	Christofide's
2405881	11	72 m	92 m	72 m	80 m	10 ms	10 ms	9 ms	23 ms	100 m	28%	28%	Christofide's
2405884	11	109 m	109 m	97 m	96 m	10 ms	11 ms	10 ms	18 ms	126 m	23%	24%	LKH
2411404	11	92 m	96 m	94 m	92 m	13 ms	9 ms	22 ms	19 ms	132 m	29%	30%	LKH
2418882	11	93 m	87 m	89 m	88 m	8 ms	7 ms	12 ms	33 ms	104 m	14%	16%	2-opt
2401806	12	122 m	110 m	110 m	109 m	12 ms	11 ms	11 ms	38 ms	131 m	16%	17%	LKH
2403790	12	105 m	119 m	109 m	103 m	12 ms	11 ms	16 ms	32 ms	139 m	22%	26%	LKH
2401230	13	118 m	112 m	106 m	106 m	24 ms	22 ms	27 ms	35 ms	127 m	17%	17%	Christofide's
2401987	13	103 m	117 m	105 m	100 m	14 ms	13 ms	13 ms	35 ms	124 m	15%	19%	LKH
2407208	13	68 m	66 m	74 m	88 m	6 ms	5 ms	6 ms	65 ms	79 m	6%	16%	2-opt
2411049	13	108 m	102 m	90 m	119 m	19 ms	15 ms	27 ms	37 ms	140 m	36%	36%	Christofide's
2418881	13	52 m	70 m	48 m	74 m	9 ms	6 ms	7 ms	28 ms	62 m	23%	23%	Christofide's
2385275	14	91 m	89 m	81 m	83 m	14 ms	12 ms	18 ms	58 ms	92 m	12%	12%	Christofide's
2410945	14	111 m	119 m	115 m	111 m	15 ms	17 ms	24 ms	39 ms	134 m	14%	17%	LKH
2417623	14	77 m	99 m	87 m	79 m	16 ms	22 ms	21 ms	33 ms	98 m	11%	21%	NN
2419399	14	110 m	116 m	108 m	113 m	17 ms	15 ms	21 ms	44 ms	136 m	21%	21%	Christofide's
2441067	14	89 m	89 m	75 m	161 m	19 ms	17 ms	15 ms	118 ms	88 m	15%	15%	Christofide's
2383098	15	121 m	121 m	121 m	116 m	26 ms	17 ms	25 ms	60 ms	128 m	5%	9%	LKH
2401231	15	111 m	95 m	97 m	108 m	19 ms	19 ms	15 ms	49 ms	105 m	8%	10%	2-opt
2401942	15	121 m	139 m	111 m	108 m	28 ms	20 ms	28 ms	37 ms	125 m	11%	14%	LKH
2405879	15	108 m	118 m	110 m	124 m	19 ms	17 ms	20 ms	57 ms	145 m	24%	26%	NN
2441136	15	112 m	88 m	104 m	110 m	16 ms	13 ms	28 ms	58 ms	108 m	4%	19%	2-opt
2411079	16	127 m	131 m	131 m	131 m	22 ms	26 ms	27 ms	47 ms	141 m	7%	10%	NN
2419398	16	103 m	125 m	115 m	113 m	21 ms	24 ms	19 ms	48 ms	142 m	19%	27%	NN
2441133	16	102 m	92 m	80 m	107 m	17 ms	14 ms	14 ms	38 ms	89 m	10%	10%	Christofide's
2403791	17	97 m	131 m	109 m	100 m	24 ms	24 ms	22 ms	90 ms	138 m	21%	30%	NN
2403801	17	106 m	118 m	104 m	106 m	23 ms	22 ms	31 ms	62 ms	119 m	13%	13%	Christofide's
2405175	17	112 m	106 m	106 m	110 m	23 ms	23 ms	35 ms	50 ms	128 m	17%	17%	Christofide's
2441110	17	98 m	96 m	92 m	102 m	17 ms	16 ms	17 ms	59 ms	112 m	18%	18%	Christofide's
2412864	18	97 m	103 m	97 m	107 m	37 ms	24 ms	26 ms	115 ms	112 m	13%	13%	Christofide's
2419397	18	131 m	133 m	123 m	123 m	24 ms	25 ms	21 ms	81 ms	143 m	14%	14%	Christofide's
2411036	20	100 m	114 m	94 m	135 m	33 ms	34 ms	31 ms	127 ms	127 m	26%	26%	Christofide's
2412863	20	121 m	131 m	119 m	131 m	53 ms	43 ms	57 ms	116 ms	152 m	22%	22%	Christofide's
2441062	21	76 m	80 m	72 m	120 m	27 ms	26 ms	35 ms	142 ms	95 m	24%	24%	Christofide's
2417622	22	109 m	119 m	107 m	127 m	31 ms	35 ms	32 ms	116 ms	125 m	14%	14%	Christofide's
2412844	23	110 m	102 m	100 m	112 m	37 ms	38 ms	43 ms	132 ms	123 m	19%	19%	Christofide's
2438402	23	118 m	128 m	116 m	118 m	38 ms	37 ms	40 ms	145 ms	152 m	24%	24%	Christofide's
2412845	25	108 m	120 m	104 m	128 m	48 ms	48 ms	45 ms	123 ms	117 m	11%	11%	Christofide's
2435803	30	141 m	149 m	119 m	129 m	71 ms	81 ms	60 ms	317 ms	134 m	11%	11%	Christofide's

Table A.1: Data Analysis

B Appendix B

Picker 1

Q1. What difference do you feel between pick by paper and pick by device system?

Ans: *"I see a big advantage using pick by device over pick by paper as it directs me to the exact location for the items to be picked and I do not have to roam in the entire warehouse searching for the location. It saves time over existing system as it gives me the shortest path to pick up all the items. Locations for parts coming from different company is automatically taken from the system so I do not have to look into another software to search the bin locations of these parts. It saves my overall time."*

Q2. Would you be comfortable wearing digital glasses or headphones to give you instructions for order picking process?

Ans: *"I would be comfortable wearing headphones to give me instructions all day but will not prefer digital/smart glasses as I wear glasses and would cause discomfort for me to carry out the job. I would also add that if I have pick by device and smart glasses then it would be the one system I would prefer as the details on the glasses will be very small to read and this will cause the discomfort for long hours of working."*

Q3. Do you feel this system helps you work more ergonomically and carry out more jobs per day?

Ans: *"I can definitely carry out more jobs in a day as I will be walking less compared to today's technique. It will give me a lot of comfort as I will not carry the paper list in my hand which will give me more freedom to carry out the job. It is very comfortable for me as I need not sort out the orders as the software does it automatically. I think I will be quicker in performing this job."*

Q4. Do you feel that this system helps you in avoiding picking wrong products?

Ans: *"I think it will really help me to make any picking error as I can look at the picture and compare it with the part which I am picking. It will save a lot of time in cross checking also."*

Q5. How can we improve this system?

Ans: *"I think this system can be improved based on today's scenario would be to connect this system to a printer so that I don't waste time in creating the labels by writing it. This system can also tell me when to use forklift for heavy parts as it would save lot of time."*

Picker 1

Date: 29.11.2022

Picker 2

Q1. What difference do you feel between pick by paper and pick by device system?

Ans: *"I would always use pick by device over pick by paper as there is lot of paper wasted in this process and digital system is more accurate in giving out the locations than pick by paper system. Current system lacks all the locations of the parts present in the warehouse and thus it will save my time in finding these locations. It will tell me exactly where the bin is located, and which path should I take to reach there. It will save my time a lot and I will walk less if I uses this digital system."*

Q2. Would you be comfortable wearing digital glasses or headphones to give you instructions for order picking process?

Ans: *"I am not comfortable wearing any extra device to do my job as I feel I am not free to do my job, it restricts me. Wearing any device for 8hrs of shift is not what I would sign up for. Also, I feel if I wear glasses or headphones I will be distracted by the system and would not look for other pickers using heavy equipment's like cranes and forklifts which can cause severe accidents. I will stick to this system definitely as I will be more aware of my surroundings plus, I can take some decisions which are beyond the scope of any software."*

Q3. Do you feel this system helps you work more ergonomically and carry out more jobs per day?

Ans: *"Yes. I have used this system and I walk less. I do not have to sort out orders in the morning. I do not have to worry if the location is not printed on the paper. Hence, I feel more comfortable using this device as my both hands can work and do the job more efficiently."*

Q4. Do you feel that this system helps you in avoiding picking wrong products?

Ans: *"Of course. Pictures help me a lot to pick the correct item. I have made picking errors in the past but with this system I feel I will not make any as I compare the parts with the pictures given on the screen before picking them."*

Q5. How can we improve this system?

Ans: *"I wish this is integrated with the inventory system in SAP and can update as soon as I pick parts from the warehouse. There are times when the system shows there are parts no parts present but actually there are parts present. Also I feel this should communicate with the assembly line orders because they have higher priority to pick parts than spare parts department."*

Picker 2

Date: 29.11.2022

Picker 3

Q1. What difference do you feel between pick by paper and pick by device system?

Ans: *"My opinion is we will become more productive with the device system. The system shows us the shortest way to pick all the requested spare parts. The way we walk is visualised on the screen installed on the cart. We also get the sorted storage bins even for the C-parts, with pick by paper we have had to find the storage bins for those parts in the access system."*

Q2. Would you be comfortable wearing digital glasses or headphones to give you instructions for order picking process?

Ans: *"Yes I would love to try new technology with smart glasses but I cannot wear it for 8 hours continuously. I would also love if pick by device system is still present giving all the information relevant to picking and glasses to show me the path."*

Q3. Do you feel this system helps you work more ergonomically and carry out more jobs per day?

Ans: *"I am sure if this system is used daily we will be able to to raise our productivity by 15% to 20% for the picking process."*

Q4. Do you feel that this system helps you in avoiding picking wrong products?

Ans: *"Yes, we have the visualisations of the path to be walked on. The material number, picture of the item, the amount of pieces to be picked is all displayed on the screen. I feel that this will make picking error almost 0 is the system works fine."*

Q5. How can we improve this system?

Ans: *"A new feature to be added can be a feature which somehow double checks the the items picked and can save time at the time of packaging."*

Picker 3

Date: 29.11.2022

Declaration

I hereby declare that the work presented in this thesis is entirely my own and that I did not use any other sources and references than the listed ones. I have marked all direct or indirect statements from other sources contained therein as quotations. Neither this work nor significant parts of it were part of another examination procedure. I have not published this work in whole or in part before. The electronic copy is consistent with all submitted copies.

place, date, signature