Abstracts workshop: Performance Analysis and Optimization of Warehouse Performance

Tutorial
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René de Koster (Erasmus University Rotterdam)

Title: Warehouse Robotics. Insights from Research

Abstract:
The new generation of warehouses is gradually becoming robotized. Warehouse automation started in the 1950s with AGVs, followed by automated storage and retrieval systems. Nowadays, managers can select from many different competitive robotic techniques to store and retrieve loads and to fulfil the customer orders. However, in the nearby future, robots will have to work in close collaboration with human workers. In the first part of my talk, I will give an overview of new and current automated order picking methods and systems and compare them for use and fit. I will particularly discuss cobotic systems, where people work together with robots. The second part of my talk will focus on robot sorting systems. In order to analyze all these systems, both quantitative models and empirical methods are used, but the main focus will be on quantitative models.

KEY-NOTES
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Nils Boysen (Friedrich-Schiller-Universität Jena)

Title: E-commerce warehousing and some new results on picker routing

Abstract:
In the wake of ever-increasing e-commerce sales, warehouses have evolved to technology-enriched, mission-critical fulfillment factories. This talk reviews suitable e-commerce warehouse structures such as scattered storage and robot-assisted order picking and investigates the routing problems that are to be solved within these novel warehouses. In the very core of traditional picker-to-parts warehouses is the classical picker routing problem, which equals the traveling salesman problem (TSP) but is well-known to be efficiently solvable in the parallel-aisle structure of warehouses. New warehouses require the solution of other well-known extended routing problems, such as the clustered TSP, the generalized TSP, and the prize collecting TSP. All these routing problems are well-known to be strongly NP-hard for general graphs. This talk shows how the warehouse structure impacts this complexity status and how the parallel-aisle structure of warehouses can be exploited to improve the efficiency of routing algorithms.

Kees Jan Roodbergen (University of Groningen)

Title: Advances in solving the storage location assignment problem

Abstract:
The problem of choosing appropriate storage locations for products in a warehouse is called the storage location assignment problem. This problem shows similarities with the Assignment Problem, a fundamental problem from the field of Operations Research. Both problems require the matching of objects from two equally-sized mutually-exclusive sets, in our case a matching of products to locations. However, the two problems differ strongly in their objective functions. The objective function of the standard Assignment Problem has a simple structure, which makes the problem

solvable in polynomial time. The storage location assignment problem, on the other hand, has the objective to minimize the average route length traveled by the workers (order pickers) while retrieving products from locations in the warehouse. This results in a complex function that depends on the layout of the warehouse, the routing method employed, the demand frequencies of all products, and the product-to-location assignment itself.

The focus in this presentation is on storage location assignment methods for class-based storage, i.e., where all products are divided into a number of (often two or three) classes based on demand frequency of the products. The fastest moving products are usually called A-items. The next fastest moving products are called B-items, and so on. Each class needs to be assigned to a dedicated part of the warehouse, but assignment within the class is assumed random with equal probability. We highlight challenges and approaches in formulating and solving the storage location assignment problem, including our novel approach for zone sizing by means of machine learning.

Debjit Roy (India Institute of Management Ahmedabad)

Title: Stochastic Models for Integrated Warehousing Systems: Modeling Constructs and Research Opportunities in Order Fulfillment

Abstract:
With growth in e-commerce, several warehouses have increasingly been automated and robotized. E-commerce order fulfillment faces numerous pressures such as coping with stringent delivery due times, managing both single and multi-line order picking, and addressing fluctuations in demand and handling capacity requirements. New automation technologies are improving the speed and flexibility of warehouse operations. Most repetitive upstream processes in the warehouses such as storage and retrieval of standardized pallet loads and totes are increasingly being automated using flexible technologies such as shuttles and lifts. Downstream order picking processes are also being automated using robots and ergonomic pick stations. Systems have evolved where human pickers collaborate with Autonomous Mobile Robots (AMRs) in order picking. Likewise, manual sorting of packages that involve labor-intensive repetitive processes are being automated using robotic sortation systems. While technologies offer performance improvement opportunities, optimal design parameter settings for integrated systems are often not explored and optimized. Furthermore, performance optimization of subsystems may not yield system-level benefits. In this talk, we will discuss developments in integrated stochastic models for warehousing systems with applications in e-commerce order fulfillment.

TALKS FROM INDUSTRY:
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Denis Pogosov (Principal R&D Engineer, Vanderlande)

Title: Towards optimized bufferization: Retrieval-efficient storage and batch movement in warehouses.

Abstract:
Traditional warehouse logistics prioritize storage, often overlooking streamlined retrieval strategies over multiple bufferization location. This presentation spotlights the challenges of multiple-order bufferization across different storage sizes. We discuss the strategic placement of items based on retrieval sequences, along with the decision to utilize or even move entire buffers or batches. By

highlighting these challenges, we aim to encourage innovative solutions for the modern warehouse management.

Erik van Wunnik (Global Director Product Development, DSV)

Title: What is the value of a Digital Twin of a warehouse operation?

Anke Simons (Junior consultant, CQM)

Title: The challenges of smart warehousing in practice

Abstract:
Smart Warehousing is the smart design and management of your logistics process. This allows you to significantly improve the productivity, capacity and efficiency of logistics. Hardware (robotization/mechanisation) is part of this. But smart management with decision support systems and operational software is just as essential for a successful approach. It is crucial to gain insight into the logistics operation and the most important drivers of this operation by means of realization data. These insights can then be translated into practical planning solutions and custom algorithms. In this presentation I will talk about some of the challenges in smart warehousing and how data science can add value.

TALKS FROM ACADEMIA:
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Vinh Dang (Eindhoven University of Technology)

Title: Order Release Strategies for a Collaborative Order Picking System

Abstract:
A collaborative order picking system (COPS) enables human-robot collaboration by using order pickers for picking and autonomous mobile robots (AMRs) for transporting load carriers. Owing to the potential performance enhancement compared to a traditional manual order picking system, COPSs are gaining momentum in the retail warehousing sector. This work proposes order release strategies based on priority and dispatching rules to achieve the best pick rate performance per AMR. A discrete event simulation model is developed to facilitate the evaluation of the proposed strategies. Their effectiveness is demonstrated with the use of real-world data from a case study warehouse. Our computational results show that a COPS using proposed strategies significantly improves the pick rate performance compared to the current practice

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Tim Engels (Eindhoven University of Technology)

Title: Stochastic analysis of milk-run systems

Abstract:
Milk-run systems are advanced batch picking systems in which the batches are made in real time. During the picking cycle, the picker is continuously updated on requested items, which they then pick. To do this, the picker walks a fixed route along all aisles and locations, picking any requested item they encounter. After each cycle, the picked items are disposed of at the depot, which are then

sorted. This system allows for a fast response time to orders and saves up worker travel time, especially in warehouses with high arrival rates.

In this talk, we relate milk-run systems to polling models; a queueing system in which a server switches between queues and serves customers in these queues. In the many-queue case, this can be accurately approximated by a continuous polling system, where customers no longer queue at given queues, but obtain locations on a circle. The server moves at a fixed speed over this circle, serving any customers they encounter. Using a mean-value analysis we propose an intricate analysis of the mean delivery times in such a system.

Negin Jamili (Erasmus University)

Title: Collaboration and Resource Sharing in Warehouses

Abstract:
My research investigates the benefits of collaboration in warehousing, focusing on the optimization of internal resources in multi-client warehouse environments.
The first paper explores the impact of collaboration on order pickers and dock doors within such warehouses. Utilizing an Integer Linear Programming (ILP) formulation, it minimizes shipping truck tardiness while evaluating collaboration's performance improvements based on operational data from a retailer. The study finds that collaboration significantly reduces trucks tardiness, mainly due to pickers than sharing the dock doors. Moreover, the highest benefits occur at medium-level resource utilization, emphasizing the value of collaborating on complementary resources.
The second paper studies the service provider perspective within multi-client warehouses and examines the sharing of key internal resources like labor (order pickers and sorters) and pick storage space (zones). By considering labor and space costs and service level agreements, the research identifies optimal resource-sharing configurations based on warehouse characteristics and client demand levels. Notably, low-demand clients benefit from resource sharing, while high-demand clients prefer dedicated resources. These findings offer strategic insights for WSPs to minimize costs, enhance service quality, and attract clients through competitive pricing policies, ultimately fostering business growth and expansion.

Timo Lehmann (Karlsruhe Insitute of Technology)

Title: Rack optimization for multi-deep robotic compact storage and retrieval systems with class based storage

Abstract:
Compact storage systems are widely available in the industry as for example multi-deep automatic storage and retrieval or robotic compact storage and retrieval systems. Multi-deep storage systems have the advantage that multiple storage loads can be stored behind or above each other, which leads to higher space utilization. However, blocking loads must be reshuffled if a retrieval load is blocked, which reduces the system’s throughput capacity. This work introduces two types of multi-deep storage systems (automatic storage and retrieval and robotic compact storage and retrieval systems) and presents throughput models for both. Both models have in common that they apply class-based storage, use nearest neighbour movements and allow multiple loads per article. Throughput models are based on a closed queuing network and reshufflings are calculated using Markov Chains. Both models are validated with discrete event simulation and verified with industry

data of an existing rack. Subsequently, a rack optimization to minimize the footprint of the rack given the desired throughput in application.

Thomas de Lombaert (Hasselt University)

Title: From centralization to worker autonomy: empowering order pickers in warehouse decisions

Abstract:
Warehouses play a vital role in a company's supply chain and contribute to its failure or success. Multiple activities are performed in a warehouse, but research has shown that order picking is by far the costliest. Therefore, warehouse managers aim at attaining high efficiency levels regarding their order picking system. With the advent of Industry 4.0, central planning tools are playing an important role in warehouses, recognized for their contribution to enhancing operational efficiency through decision support. However, those (algorithmic) operational directives partly erode the order pickers' perceived autonomy, which is one of the three basic psychological needs and affects worker well-being. This study presents the development, testing, and post-hoc evaluation of an autonomy-increasing intervention in a real-world warehouse. We show that granting more decision autonomy to order pickers has a beneficial impact on their individual well-being as well as organisational outcomes.

We developed an order assignment mechanism (OAM) in which order pickers can choose their next order from an order set. This novel OAM was tested during an experiment in a real-world warehouse from a major Belgian logistics service provider. We used a within-subjects study design and evaluated the outcomes in a holistic manner, as psychosocial-, physical-, and performance-related outcome measurements were collected. In total, 18 order pickers participated in our study. The results indicate a significant increase in psychosocial worker well-being, as well as positive, albeit non-significant, enhancements in physical well-being due to our OAM. Productivity measurements remain steady. We also conducted semi-structured interviews to delve deeper into our results. These interviews reveal a very high user-experience and a keen desire to adopt the newly-proposed OAM.

Our study shows that high efficiency levels can coincide with increased worker well-being. Using a holistic evaluation approach, we show the beneficial impacts of an autonomy-increasing intervention in a real-world warehouse. The insights derived from this study can be translated to other warehouse planning problems and give rise to several subproblems which ought to be encountered with an OR perspective.

Bhoomica Nataraja (Eindhoven University of Technology)

Title: To Batch or Not to Batch? Optimizing Order Fulfillment using DRL

Abstract:
Recent trends in e-commerce show a substantial increase in demand. Customers order more and smaller orders and expect delivery in shorter lead times. To meet these evolving demands, warehouses are turning to robotics and automation. This study explores the critical decision-making process in an autonomous robot-based order-picking and packing system. Specifically, we address two key questions: (1) when to pick an order and (2) which orders to batch for picking. Our objective is to minimize the weighted earliness and tardiness in order fulfillment. These two metrics are often equally important, as earliness incurs costs related to holding, opportunity costs, and deterioration of perishable goods, while tardiness impacts customer satisfaction. We employ a Semi-Markov Decision

Process and implement a Deep Reinforcement Learning (DRL) agent, trained using the Proximal Policy Optimization algorithm. This agent interacts with a discrete event simulation to make real-time decisions. We develop three distinct agents with varying complexity to answer the pivotal questions: when to batch and pick and which orders to batch. These agents are rigorously evaluated against traditional and advanced benchmarks across different demand scenarios. Our findings demonstrate that most agents outperform conventional methods, with one agent even surpassing advanced baseline methods.

Farzaneh Rajabighamchi (Maastricht University)

Title: Graph reduction for the Steiner Travelling Salesman Problem in a planar grid-graph. An application in order picking in multi-block layout warehouses

Abstract:
This paper presents an improved graph reduction algorithm for solving the Steiner Travelling Salesman Problem (TSP) in a planar grid-graph applied in the order picking problem. In the presented algorithm, first the Steiner TSP is transformed into a TSP and after that, by the means of pre-processing, unnecessary arcs are removed from the TSP graph. Finally, the reduced TSP graph is solved with the TSP formulation. Transforming the STSP into the TSP can offer several advantages, such as simplicity, better performance, and use of existing solution algorithms in the literature since TSP is a well-studied and widely known problem in optimization. This algorithm is applicable on any other problem with planar grid graph. The algorithm heavily relies on graph reduction techniques: it removes unnecessary vertices and edges from the planar graph that are not necessary in the optimal solution. As a result, we achieve a significant increase in calculation speed and reduction in the running time. The order pickers routing problem entails collecting items from storage in response to customer requests. We use the Traveling Salesperson Problem (TSP) to optimize the routes taken by order pickers. In the literature, exact algorithms — typically based on dynamic programming — only exist for small warehouses with a small number of blocks, while for larger warehouse layouts mainly heuristic and meta-heuristic methods are provided. The presented graph reduction method allows us to adequately solve larger — more realistic — instances in a short amount of time. Our algorithm is tested on different problem instances from the literature and its performance is reported and compared with the current state-of-the-art. We conclude that our algorithm outperforms existing algorithms in terms of simplicity, size and calculation time.

Arpan Rijal (University of Groningen)

Title: Dynamics between warehouse operations and vehicle routing

Abstract:
When scheduling the distribution of ordered items from a warehouse to customers, the transportation planning is generally done first and serves as input for planning warehouse operations. Such a sequential approach can lead to substantial inefficiencies when the customer deliveries are restricted by time windows, and the warehouse has limited resources available (both order pickers and space in the staging area). This paper studies the trade-offs between warehouse operations and transportation planning. The goal is to understand the impact of three specific managerial interventions: adopting an integrated planning approach, expanding the available staging space, and expanding the delivery time windows. To this end, we propose a mathematical model for a general vehicle routing problem that incorporates order batching, order picker scheduling, staging, and vehicle loading. We introduce a novel idea to express the picking time of an order batch as a

function of the batch size and develop a metaheuristic to solve this integrated problem. Furthermore, we develop exact algorithms to provide optimal solutions for the individual warehouse and transportation problems in a sequential planning approach. Managerial insights are distilled from case studies in two warehouses, one for ambient products and the other for refrigerated products, of a leading grocery retailer in the Netherlands. Our results show that integrated planning outperforms the other managerial interventions and generates cost savings between 9% and 11%. Savings are generally realized by executing larger order batch sizes to be picked in the warehouses at the expense of additional routing cost (around 2–3%). The second intervention in the form of time window expansions of only 15 minutes for customer deliveries can lead to cost savings between 4% and 6%, which results from a reduction in both transportation and warehousing cost. Expanding the capacity of the staging area is only meaningful when the staging space is highly utilized and only results in cost savings for the warehouse operations.

Lin Xie (University of Twente)

Title: Reinforcement learning for picker routing in mixed-shelves warehouses

Abstract:
In recent years, machine learning (ML) algorithms for combinatorial optimization (CO) problems received a surge of attention. While early approaches failed to outperform traditional OR methods, the gap between handcrafted and learned heuristics has been steadily closing. Especially the employment of more advanced network architectures and learning algorithms as well as their combination with search strategies like beam search have led to on-par results for many CO problems like TSP and VRP. Yet, the performance aspect is not the only reason why OR and ML researchers deem neural CO (NCO) promising. One of the main advantages of using ML to solve CO problems is the reduction in running time compared to heuristics. Many applications require quick solutions obtained within reasonable time frames which cannot be provided by extensive search algorithms and exact solvers.

One such application is picker routing in warehouses where short-term changes due to sick leave or canceled customer requests might require fast changes to the current plan. In order to improve routing efficiency, we combine two methods in our problem, namely allowing split orders and using mixed-shelves storage. Splitting concept allows orders can be picked up in different tours while items of the same stock keeping unit (SKU) are spread over the shelves, leading to multiple storage locations per SKU in mixed-shelves warehouses. Pickers can then decide between these alternative locations when collecting the items demanded by customers. Our picker routing problem in mixed-shelves warehouses can be formulated as a VRP problem that incorporates the selection of picking items within each tour and the selection of alternative storage locations.

Current NCO literature does not cover such VRP variant. Therefore, in this work we develop a transformer-based neural network which we train using the REINFORCE algorithm to obtain short picker routes in mixed-shelves warehouses. For small test instances for which we were still able to generate exact solutions, our method finds optimal or near-optimal solutions within seconds. We therefore contribute to the field of NCO by applying this emerging technology to a new problem which is more complex than the standard problems used for benchmarking in existing NCO literature.

Yinggian Zhang (Eindhoven University of Technology)

Title: Learning efficient and fair policies for collaborative human-robot order picking

Abstract:
In collaborative human-robot order picking systems, human pickers and Autonomous Mobile Robots (AMRs) travel independently through a warehouse and meet at pick locations where pickers load items onto the AMRs. In this work, we consider an optimization problem in such systems where we allocate pickers to AMRs in a stochastic environment. We propose a multi-objective deep reinforcement learning (DRL) approach to learn good allocation policies to maximize pick efficiency while also aiming to improve workload fairness amongst human pickers. In our approach, we model the warehouse states using a graph, and define a network architecture that captures regional information and extracts information from efficiency and workload features effectively. We develop a discrete-event simulation model, which we use to train and evaluate the proposed DRL approach.
In the experiments, we demonstrate that our approach can find non-dominated policy sets that outline good trade-offs between fairness and efficiency. The trained policies outperform the benchmarks in terms of efficiency and fairness, and moreover, they show good transferability properties when being tested with different scenarios in different sizes of the warehouse.