

## Warehouse design and management

René B. M. De Koster<sup>a</sup>, Andrew L. Johnson<sup>b,c</sup> and Debjit Roy<sup>a,d\*</sup>

<sup>a</sup>Rotterdam School of Management, Erasmus University, Rotterdam, Netherlands; <sup>b</sup>Industrial and Systems Engineering, Texas A&M University, College Station, TX, USA; <sup>c</sup>School of Information Science and Technology, Osaka University, Osaka, Japan; <sup>d</sup>Indian Institute of Management, Ahmedabad, India

(Received 25 July 2017; accepted 25 July 2017)

Warehouse design and operations have undergone major changes over the past decades. In particular, with the onset of e-commerce, the complexity of warehouse operations has increased multi-fold with the storage of large SKU assortment in small quantities, volatile demand patterns and primarily single-line customer orders. They have grown in size due to consolidation, new and fast identification and communication technologies have found their way into the warehouse and process automation technologies have progressed improving speed and operational efficiencies. In line with these developments, this special issue pays attention to new technologies and methods and how they impact warehouse design and management.

**Keywords:** warehouse design; operations; order picking; new technologies

### Introduction

Warehouses play a critical role in matching product demand with supply across different echelons in the supply chain. No supply chain design and management is adequate without deciding the location, design and management of warehouses. Today, warehouses operate not only as centres for storage but also as centres for value-addition. Several warehouses have assembly, packaging and repair operations within their premises. Warehouse decision models are crucial for an organisation's profitability. Existing research shows that understanding warehouse design and management principles can play a pivotal role in improving the efficiency of operations; reducing employee fatigue and turnover; and improving customer service levels. New warehouse automation systems can help increase operational flexibility and cater growing customer expectations.

The research agenda in warehousing includes optimisation-based decision models for addressing strategic, tactical and operational warehouse problems, performance analysis of both manual and automated warehouse systems (including robotised systems) using stochastic models, new warehouse design principles, behavioural operations management in warehouses, tools for managing complex e-commerce warehouse operations such as managing returns, cost models for selection of automated material handling solutions, warehouse safety and security, warehousing contracts, etc. Recently, several conferences have been organised around these themes such as the International Material Handling Research Colloquium, June 2016, in Germany, the tracks at the annual EURO and Informs conferences or at the 15th IFAC Symposium on Information Control Problems in Manufacturing, Ottawa, Canada ([incom2015.org](http://incom2015.org)). Over time (the journal celebrates its 55th volume anniversary this year), the International Journal of Production Research has proven to be one of the key outlets for promoting research in warehouse design and management.

A literature search in the International Journal of Production Research since 1997 (using Google Scholar with the Keywords 'Warehousing' and any of the key words 'order picking', 'batching', 'zoning', 'layout', 'routing', 'storage', 'retrieval', 'technology', or 'design') yields over 100 papers. The relevant papers with most citations/year are listed in Table 1, whereas the count of published articles in International Journal of Production Research related to warehousing area is shown in Figure 1. An increasing trend in the publication count suggests that there is a growing interest of the researchers in warehousing.

The above table shows that a focus on improving order picking efficiency in conventional warehouses through improved warehouse layout, batching, storage assignment and picker routing has received much attention from researchers. In addition, automated technologies, such as compact storage systems, AS/R and AVS/R systems, have

\*Corresponding author. Email: [debjit@iima.ac.in](mailto:debjit@iima.ac.in)

Table 1. Top-cited (per year) warehouse publications in IJPR since 1997. Executed on 14 June 2017.

Paper	Subjects	Citations	Citations/year
Grosse et al. (2015)	Human factors in order picking planning	61	20.3
Roodbergen and De Koster (2001)	Routing, layout	310	18.2
De Koster, Van der Poort, and Wolters (1999)	Order batching	235	12.4
Heragu et al. (2005)	Design, product allocation	149	11.5
Caron, Marchet, and Perego (1998)	Routing, product allocation	206	10.3
Le-Duc and de Koster (2005)	Routing, product allocation, zoning, travel distance	125	9.6
Tsai, Liou, and Huang (2008)	Order batching, picking, travel distance, due time	84	8.4
Gagliardi, Renaud, and Ruiz (2012)	AS/RS, models, literature review	48	8
Grosse, Glock, and Neumann (2017)	Human factors, order picking, literature review	8	8
Caron, Marchet, and Perego (2000)	Layout, order picking	143	7.9
Vaughan (1999)	Layout, order picking	150	7.9
Lerher (2016)	AVS/R system, travel time	15	7.5
Wang, Chen, and Xie (2010)	Storage/retrieval, WMS, RFID	58	7.3
Ekren and Heragu (2010)	Layout, AVS/R system	57	7
De Koster, Le-Duc, and Yu (2008)	Layout, compact storage, AS/RS	66	6.6
Hwang, Oh, and Lee (2004)	Routing, order picking	92	6.6

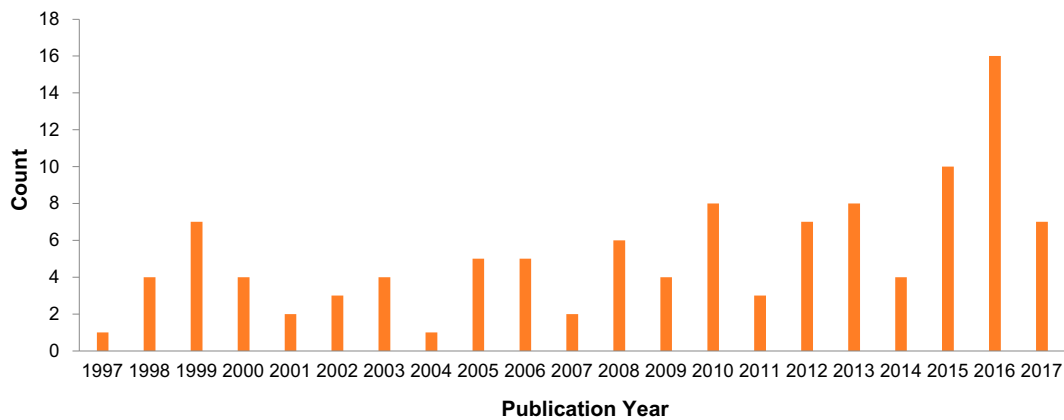


Figure 1. Count of warehouse publications in IJPR since 1997. Executed on 14 June 2017.

received a growing interest. Two recent publications by Grosse et al. (2015) and Grosse, Glock, and Neumann (2017) focus on human factors in order picking, a topic which also is receiving increased interest.

The focused issue on Warehouse Design and Management intends to reflect these trends, efforts and results. The papers address contemporary challenges in warehouses, particularly related to warehouse design, organisation of order picking, warehouse slotting, staffing, life cycle planning (for both products and the environment), automation and transportation between storage locations in ports. We introduce the papers included in this special issue below.

### Papers in the special issue

In their paper *A Hierarchical Approach to Warehouse Design*, Timothy Sprock, Anike Murrenhoff and Leon F. McGinnis propose a hierarchical design decision support methodology for warehouses, based on decomposing the design problem into a set of subproblems and using a formal model of the system to integrate the solutions to these subproblems. The methodology enables a thorough search of the design space and the identification of candidate designs for consideration by the designer. The design methodology is demonstrated with an example of designing a forward pick area.

Christoph H. Glock, Eric H. Grosse, Ralf M. Elbert and Torsten Franzke study maverick order picking behaviour, or workplace deviance (either in a positive or negative sense), in their paper *Maverick picking: The Impact of Modifications in Work Schedules on Manual Order Picking Processes*. Maverick picking can influence the performance of the picking process. Their paper studies its causes, its forms of appearance and the potential impact on performance. Their results, based on a multi-case study, support the proposition that maverick picking is a major determinant of order picking performance.

Thomas Chabot, Rahma Lahyani, Leandro C. Coelho and Jacques Renaud study order picking routing in their paper *Order Picking Problems under Weight, Fragility and Category Constraints*. They include product-specific constraints that are often neglected, such as weight, fragility and category constraints. They present four heuristic methods, including extensions of the classical largest gap, midpoint and S-shape heuristics, as well an adaptive large neighbourhood search algorithm. They show their ALNS method outperforms the other heuristics and that it has tight gaps with two mathematical models.

To meet strict delivery deadlines in a volatile demand environment such as e-commerce, a good plan of worker requirements is crucial. Teun van Gils, Katrien Ramaekers, An Caris and Mario Cools propose time series-based models to accurately forecast the daily number of order lines in a warehouse, in their paper *The Use of Time Series Forecasting in Zone Order Picking Systems to Predict Order Pickers' Workload*. Using a real case study, they show that such information can be very useful to estimate the number of order pickers and also assign them to pick zones.

E-commerce warehouse operations have to cope with large fluctuations in customer order volumes and a large proportion of product returns. Hence, optimal policies for traditional manual warehouses may not be suitable for e-commerce warehouses. To address this gap, Albert H. Schrottenboer, Susanne Wruck, Kees Jan Roodbergen, Marjolein Veenstra and Arjan S. Dijkstra study the optimal pick routes in their paper titled *Order Picker Routing with Product Returns and Interaction Delays* using a hybrid genetic algorithm. The algorithm determines routes for simultaneous pickup of products in response to consumers' orders and delivery of returned products to storage locations.

Order picker discomfort is of significant concern in manual order picking process and is often ignored while identifying the best item storage location. José A. Larco Martinelli, René B.M. De Koster, Kees Jan Roodbergen and Jan Dul attempt to address this gap in their paper titled *Managing Warehouse Efficiency and Worker Discomfort through Enhanced Storage Assignment Decisions*. They propose an elegant two-stage solution methodology to address these dual objectives. In the first stage, they build data-driven empirical models for estimating cycle times and workers' discomfort. In the second stage, the empirical models are adopted to formulate a bi-objective assignment problem for assigning products to storage locations. The model is tested for two real facilities.

Puzzle-based storage systems are a new type of automated storage systems that allow storage of unit loads in a rack on a very small footprint with individual accessibility of all loads. Such systems are already adopted for dense parking, dense storage in vessels and new warehousing applications are at the horizon. Masoud Mirzaei, René B.M. De Koster and Nima Zaerpour develop an optimal method to retrieve two loads simultaneously in their paper titled *Modelling Load Retrievals in Puzzle-Based Storage Systems*. They also develop a heuristic approach for efficiently retrieving more than two loads. Such algorithms hold promise for practice because they can reduce the travel time by more than 15%.

Optimising space utilisation is one of the main goals in warehouse design and operation. While block-stack storage is an inexpensive storage system widely used in manufacturing operations for storing pallets, the optimal storage layout dimensions under a finite production rate are still unknown. In their paper titled *Optimising Space Utilisation in Block Stacking Warehouses*, Shahab Derhami, Jeffrey S. Smith and Kevin R. Gue propose mathematical models to obtain the optimal lane depth. They use a simulation model to analyse the layout performance with stochastic input parameters.

While Van Gils et al. use time series forecasting models to plan order picker capacity under uncertain demand, Susanne Wruck, Iris F.A. Vis and Jaap Boter propose five different multi-stage stochastic programming approaches suitable for planning full-time and flexible staff for order pick activities in their paper *Risk Control for Staff Planning in e-commerce Warehouses*. The models that deal with uncertainties are known from their use in financial risk management and other application areas. Using a Dutch e-commerce warehouse, they show that the multi-period conditional value at risk appears to be most promising for volatile demand conditions.

Often warehouses will carry products with varying life cycles. This product selection strategy can have important benefits in terms of smoothing demand and cash flows, but the implications for warehouse operations are often a secondary thought or not considered. Bradley Guthrie, Pratik Parikh and Nan Kong investigate this issue in *Evaluating Warehouse Strategies for Two-Product Class Distribution Planning* for three common distribution strategies and propose an alternative. The potential benefits are shown through simulation.

While there are several new innovations in automated warehousing systems and technologies, little is known about the approaches to systematically assess the carbon footprint of warehouse operations. In the paper titled *Environmental Impact of Warehousing: A Scenario Analysis for the United States*, Jörg M. Ries, Eric H. Grosse and Johannes Fichtinger suggest a classification scheme that enables researchers and practitioners to systematically assess warehouse-related energy consumption and emissions in order to measure the CO<sub>2</sub> footprint of warehouse operations. In addition, they identify effective emission mitigation strategies for decarbonising warehousing operations using US warehouse data.

Automated order fulfilment systems are often difficult to model because there are many components interacting. Yingying Wu, Chen Zhou, Yaohua Wu and Xiang T. R. Kong in their paper *Zone Merge Sequencing in an Automated Order Picking System* tackle this problem for a zone automated dispensing system used widely in mail order and

catalogue order fulfilment. They formulate a mathematical model and perform sensitivity analysis to characterise the factors that affect throughput. The model is demonstrated for both simulated and real data and shows potential room for improvement over current best practices.

Automated warehouses often make use of shuttle-based storage and retrieval systems. Banu Y. Ekren investigates the design of these systems using graph-based design procedures in the article *Graph-based Solution for Performance Evaluation of Shuttle-Based Storage and Retrieval System*. From the analysis, insights are gained on the number of bays, aisles and tiers for the rack design with the primary performance metric being average cycle time. A variety of scenarios are explored via simulation.

Within a container terminal, there are a variety of transportation methods and a variety of stakeholders making the design of an inter-terminal container transport difficult. In the article, *Collaborative Solutions for Inter Terminal Transport*, Amir Gharehgozli, René B.M. De Koster and Rick Jansen analyse the design of an inter terminal container transport via simulation to estimate the cost savings per stakeholder operating in a coalition within the terminal. They apply their framework to Port of Rotterdam data and find container transports are only beneficial in high demand scenarios.

## Conclusion

The trend which was detected in the literature search in the Introduction can also be found in the current issue. Warehousing research not only focuses on traditional subjects like efficiency improvement in conventional low-level order picking situations, or classic automation systems like AS/R systems. Increasingly, attention is given to new automated technologies, like very high-density storage systems and AVS/R systems, or to other factors (like human factors) that help improve warehouse performance.

## References

- Caron, F., G. Marchet, and A. Perego. 1998. "Routing Policies and COI-Based Storage Policies in Picker-to-Part Systems." *International Journal of Production Research* 36 (3): 713–732.
- Caron, F., G. Marchet, and A. Perego. 2000. "Optimal Layout in Low-Level Picker-to-Part Systems." *International Journal of Production Research* 38 (1): 101–117.
- De Koster, R., E. Van der Poort, and M. Wolters. 1999. "Efficient Orderbatching Methods in Warehouses." *International Journal of Production Research* 37 (7): 1479–1504.
- De Koster, R., T. Le-Duc, and Y. Yu. 2008. "Optimal Storage Rack Design for a 3-Dimensional Compact AS/RS." *International Journal of Production Research* 46 (6): 1495–1514.
- Ekren, B. Y., and S. S. Heragu. 2010. "Simulation-Based Regression Analysis for the Rack Configuration of an Autonomous Vehicle Storage and Retrieval System." *International Journal of Production Research* 48 (21): 6257–6274.
- Gagliardi, J. P., J. Renaud, and A. Ruiz. 2012. "Models for Automated Storage and Retrieval Systems: A Literature Review." *International Journal of Production Research* 50 (24): 7110–7125.
- Grosse, E. H., C. H. Glock, M. Y. Jaber, and W. P. Neumann. 2015. "Incorporating Human Factors in Order Picking Planning Models: Framework and Research Opportunities." *International Journal of Production Research* 53 (3): 695–717.
- Grosse, E. H., C. H. Glock, and W. P. Neumann. 2017. "Human Factors in Order Picking: A Content Analysis of the Literature." *International Journal of Production Research* 55 (5): 1260–1276.
- Heragu, S. S., L. Du, R. Mantel, and P. Schuur. 2005. "Mathematical Model for Warehouse Design and Product Allocation." *International Journal of Production Research* 43 (2): 327–338.
- Hwang, H., Y. H. Oh, and Y. K. Lee. 2004. "An Evaluation of Routing Policies for Order-Picking Operations in Low-Level Picker-to-Part System." *International Journal of Production Research* 42 (18): 3873–3889.
- Le-Duc, T., and R. de Koster. 2005. Travel Distance Estimation and Storage Zone Optimization in a 2-Block Class-Based Storage Strategy Warehouse, *International Journal of Production Research* 43 (17): 3561–3581.
- Lerher, T. 2016. "Travel Time Model for Double-Deep Shuttle-Based Storage and Retrieval Systems." *International Journal of Production Research* 54 (9): 2519–2540.
- Roodbergen, K. J., and R. De Koster. 2001. "Routing Methods for Warehouses with Multiple Cross Aisles." *International Journal of Production Research* 39 (9): 1865–1883.
- Tsai, C. Y., J. J. H. Liou, and T.-M. Huang. 2008. "Using a Multiple-GA Method to Solve the Batch Picking Problem: Considering Travel Distance and Order Due Time." *International Journal of Production Research* 46 (22): 6533–6555.
- Vaughan, T. S. 1999. "The Effect of Warehouse Cross Aisles on Order Picking Efficiency." *International Journal of Production Research* 37 (4): 881–897.
- Wang, H., S. Chen, and Y. Xie. 2010. "An RFID-Based Digital Warehouse Management System in the Tobacco Industry: A Case Study." *International Journal of Production Research* 48 (9): 2513–2548.

Copyright of International Journal of Production Research is the property of Taylor & Francis Ltd and its content may not be copied or emailed to multiple sites or posted to a listserv without the copyright holder's express written permission. However, users may print, download, or email articles for individual use.