CROSS-DOCKING: CURRENT RESEARCH VERSUS INDUSTRY PRACTICE AND INDUSTRY 4.0 ADOPTION

Fabian Akkerman, Eduardo Lalla-Ruiz, Martijn Mes
and Taco Spitters

ABSTRACT

Cross-docking is a supply chain distribution and logistics strategy for which less-than-truckload shipments are consolidated into full-truckload shipments. Goods are stored up to a maximum of 24 hours in a cross-docking terminal. In this chapter, we build on the literature review by Ladier and Alpan (2016), who reviewed cross-docking research and conducted interviews with cross-docking managers to find research gaps and provide recommendations for future research. We conduct a systematic literature review, following the framework by Ladier and Alpan (2016), on cross-docking literature from 2015 up to 2020. We focus on papers that consider the intersection of research and industry, e.g., case studies or studies presenting real-world data. We investigate whether the research has changed according to the recommendations of Ladier and Alpan (2016). Additionally, we examine the adoption of Industry 4.0 practices in cross-docking research, e.g., related to features of the physical internet, the Internet of Things and cyber-physical systems in cross-docking methodologies or case studies. We conclude that only small adaptations have been done based on the recommendations of Ladier and Alpan (2016), but we see growing attention for Industry 4.0 concepts in cross-docking, especially for physical internet hubs.

Keywords: Cross-docking; materials handling; Industry 4.0; physical internet; systematic literature review; supply chain distribution

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INTRODUCTION

Cross-docking is a supply chain distribution and logistics strategy for minimizing long-term storage of products and parts, maximizing fleet utilization and minimizing trucks dispatches. Over the past decades, the domain has gained attention from a variety of industries, e.g., retail, automotive, perishable goods and pharmaceutics (van Belle, Valckenaers, & Cattrysse, 2012). At cross-docking terminals, cargo is typically stored for less than 24 hours. The process at the terminals consists of unloading, sorting and temporarily storing the goods of inbound trucks from suppliers, after which the goods are moved across the terminal where they are loaded on outbound trucks to be dispatched further down the supply chain.

Developments in cross-docking systems have generated competitive advantages. The market of supply chain management is becoming increasingly competitive, making it crucial to optimize logistics costs and throughput of products to stay competitive, as observed in industries such as retail chains, e.g., Walmart (Chen, Fan, & Tang, 2009), and mailing companies, e.g., UPS (Forger, 1995). Logistics-related activities are one of the main cost drivers for many industries (Gue, 2014; Wang, Ranganathan Jagannathan, Zuo, & Murray, 2017). Furthermore, the environmental impact becomes more important; for every voluntary disclosure of an additional 1000 metric carbon emissions, the value of a company deteriorates by $212,000 on average (Matsumura, Prakash, & Vera-Muñoz, 2014). Solution methods for cross-docking that quantify and minimize carbon footprints are under development (Çolak et al., 2020; Nathanail, Terzakis, & Zerzis, 2020). Hence, due to the nature of low inventory levels and higher utilization of trucks, cross-docking has found an increasing amount of attention in the domain of (green) supply chain management (Dadhich, Genovese, Kumar, & Acquaye, 2015).

There is a wide range of literature on quantitative methods to optimize various decision levels of cross-docking problems, e.g., truck scheduling (Berghman, Briand, Leus, & Lopez, 2015; Bodnar, de Koster, & Azadeh, 2015; Shakeri, Low, Turner, & Lee, 2012), vehicle routing (Ahmadizar, Zeynivand, & Arkat, 2015; Dondo & Cerdá, 2015), truck-to-door assignment (Guemri, Nduwayo, Todosijević, Hanafi, & Glover, 2019) and the shape of cross-docking terminals (Bartholdi & Gue, 2004). Due to the computational complexity of cross-docking problems, the majority of the proposed optimization models use simplifications. Often, such models do not match industry requirements, and reviews suggest an absence of implementation focus on cross-docking literature (Ladier & Alpan, 2016).

To compare what industry practices are commonly used in the literature, Ladier and Alpan (2016) conducted a review study divided into two parts: state-of-the-art literature research on quantitative solution approaches to operational cross-docking problems, and on-site research with interviews at eight cross-docking terminals. The authors constructed a framework for comparing cross-docking research with industry practice. A significant share of the quantitative studies use modelling constraints and performance measures that do not adequately reflect real-world industry practice (Ladier & Alpan, 2016). Ladier and Alpan (2016) recommended connecting future research and industry practice by changing modelling settings and performance indicators.

We aim to build on the study performed by Ladier and Alpan (2016). The survey and state-of-the-art review described above was performed in a non-systematic way. The methodology followed in that work involved that selected articles had to be written in English and include well-defined keywords, e.g., cross-dock, cross-docking, transhipment, etc. The authors limited the resulting works to the operational level, resulting in 142 papers up to the year 2015. Since then, numerous new studies have been conducted within the cross-docking domain. Hence, it is interesting to find indications if there is more presence of the practical modelling settings that were recommended for future work. Since 2016, three new literature reviews have been conducted on cross-docking. Buakum and Wisittipanich (2019) conducted a literature review on the period of 2001–2017, exclusively on what type of meta-heuristic solutions are proposed to cross-docking operational problems. The systematic literature review conducted by Ardakani and Fei (2020) extracts information about processes uncertainty for cross-docking planning. Theophilus, Dulebenets, Pasha, Abioye, and Kavoosi (2019) conducted a state-of-the-art review on the timeframe of 2016–2018 regarding the truck scheduling problem. No studies have been conducted on the intersection of research and industry practice. Thus, in this chapter, we conduct a systematic literature review in which we select papers that consider industry practice, e.g., case-based studies or studies presenting real-world data. This allows us to study whether the gap between research and industry practice has narrowed since 2016.

Furthermore, we focus on developments in academia and industry with regards to Industry 4.0. The term Industry 4.0 was coined by Kagermann and Wahlster (2011). The term is used for a new revolution in industry, after the first revolution moving from hand labour to machines (1760–1840), the second revolution in faster transport and communication using rail and telegraph (1871–1914) and the third revolution (late twentieth century) in computers and automation. The fourth revolution entails the interconnection of machines, transparency of information, the assistance of machines in human labour and autonomous decision-making of machines (Lu, 2017). Our review examines the degree to which Industry 4.0 has been adopted in academic research and the cross-docking industry.

We compare the studies obtained from our review with the state-of-the-art literature before 2015, using the same elements of the classification framework by Ladier and Alpan (2016), i.e., cross-docking settings, business process level and performance indicators. Indications of change or absence of change are used to recommend starting points for future reviews and future implementation-oriented studies. Unlike Ladier and Alpan (2016), we follow a systematic literature review primarily focused on the literature published in the period 2015–2020 and do not conduct interviews with cross-docking managers. Thus, the contributions of this chapter are (1) the summary of new works on cross-docking in the period 2015–2020, (2) the review of changes in literature since 2016, (3) the review of Industry 4.0 adoption in cross-docking research and (4) recommendations for future research in cross-docking and Industry 4.0.

The remainder of this chapter is structured as follows. First, cross-docking in the Industry 4.0 era is further explained in Section 'Cross-Docking in the Industry 4.0 Era'. Next, the methodology for the systematic literature review is explained in Section 'Methodology'. In Section 'Results', the outcomes of the systematic literature review are presented. Finally, we discuss our findings in Section 'Discussion', conduct a complementary literature review of Industry 4.0 in cross-docking in Section 'Extended Search on Industry 4.0 in Cross-Docking' and draw conclusions in Section 'Conclusion'.

CROSS-DOCKING IN THE INDUSTRY 4.0 ERA

Cross-docking is typically defined as the process of consolidating less-than-truckload (LTL) shipments with the same destination to full truckloads (FTL), with the additional trait that products are stored up to a maximum of 24 hours (Boysen & Fliedner, 2010). The processes at cross-docking terminals generally constitute unloading of inbound trucks, checking, sorting, temporary storage, transhipment across the terminal and loading into outbound trucks. We give an overview of cross-docking decisions in Section 'Cross-Docking Research and Industry Practice'. Next, we introduce Industry 4.0 and its potential for cross-docking in Section 'Industry 4.0 Components in Manufacturing and Logistics'.

Cross-Docking Research and Industry Practice

Cross-docking allows consolidation of many LTL shipments into fewer FTL trucks, transporting the variety of products or parts in a network of consumers, warehouses and producers. Furthermore, the trait of 24-hour maximum storage time enables a feasible production and transportation strategy for industries with perishable products, e.g., food or pharmaceutical industries.

Successfully implementing cross-docking operation strategies into an organization requires changes to business model and operations (Stephan & Boysen, 2011), e.g., finding the operational gains of cross-docking, analyzing network integration suitability and evaluating possible negative effects, e.g., delayed delivery times on customer satisfaction and double-handling costs. Successful implementation of cross-docking into a company's supply chain seeks to eliminate and reduce redundant operations, e.g., storage and movement of products (Enderer, Contardo, & Contreras, 2017). Since the 1980s, several cross-docking studies were done, following the industry trend. Only after 2004, cross-docking started to receive significant attention in the scientific literature (van Belle et al., 2012; Ladier & Alpan, 2016). Over the past three decades, numerous studies have been conducted on the feasibility and benefits of implementing cross-docking for various industries, e.g., the pharmaceutical branch (Ponikierska & Sopniewski, 2017), automotive industry (Witt, 1998), food industries (Vasiljevic, Stepanovic, & Manojlovic, 2013), retail (Benrqya, 2019; Buijs, Danhof, & Wortmann, 2016) and online retail (Cattani, Souza, & Ye, 2014).

To benefit from incorporating cross-docking operations in supply chains, it is recommended to adopt a more holistic approach to supply chain management than traditional warehousing (Vogt, 2010). Employing cross-docking operations implies almost eliminating the storage buffer in a distribution network. The local cross-docking operation efficiency is interdependent with distribution activities across the supply chain network. Planning across the entire supply chain is crucial, and the models that include uncertainty are indispensable for coping with disturbances in the supply chain network (Ardakani & Fei, 2020).

Introducing cross-docking terminals allows for a reduction in the number of trips for the truck fleet (Buijs, Vis, & Carlo, 2014). Initially, each of the suppliers producing unique products would often directly ship LTL batches of their product to each of the costumers or a long-term storage warehouse. These customers are sometimes located in high-traffic city hubs or other types of urban areas for industries like retail or foods. Last-mile delivery often takes a significant time (Nathanail et al., 2020). By introducing the intermediate stop at a cross-docking terminal, all suppliers deliver shipments less frequently, and the products are consolidated in FTL trucks according to the specific customer demands. Fig. 1 illustrates the difference between classical direct transport (left) and transport using cross-docking (right). Additionally, the decisions for cross-dock location and vehicle routing are indicated.

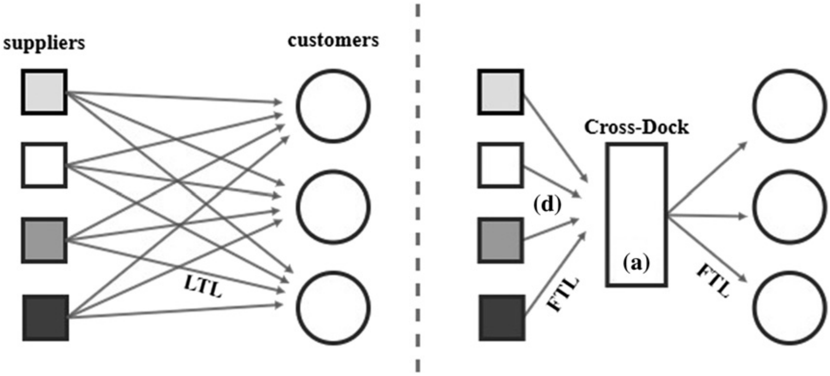


Fig. 1. Schematic Representation of a Classical Supply Chain and a Cross-Docking Supply Chain; the Meaning of the Cross-Docking Decision Levels: (a) Cross-Dock Location Selection and (d) Vehicle Routing Decision.

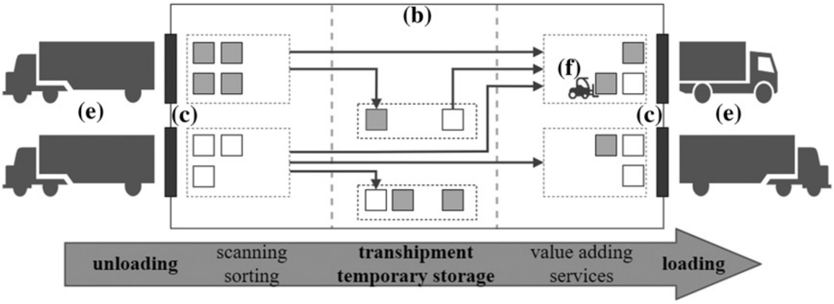


Fig. 2. Schematic Representation of an I-Shaped Cross-Dock, Decision Levels: (b) Design and Terminal Layout, (c) Door Policy and Assignment, (e) Truck Scheduling and (f) Internal Resource Scheduling.

Truck scheduling and internal procedures vary per industry. Fig. 2 illustrates a general structure of a cross-docking terminal. The letters in Figs. 1 and 2 represent the decision-making levels for the cross-docking distribution strategy.

Typically, cross-docking problems have been classified into three levels of decision-making: strategic, tactical and operational. We utilize a rephrased definition of the three levels applied to cross-docking as introduced by van Belle et al. (2012).

Strategic decisions in this context deal with the location and layout of cross-docking terminals. Location planning is centred around the decisions regarding the structure of the distribution network and the locations of cross-docking terminals. The design and layout of the terminal concern the physical characteristics, i.e., shape and the number of doors. Building shapes are often indicated by a letter, e.g., I, X, L or T. A comparison of the various building design choices of a cross-docking terminal can be found in Bartholdi and Gue (2004). Furthermore, for optimal building selection and cost-to-quality real-estate acquisition, there are models in development that take a company's specific needs and variables into account (Baglio, Perotti, Dallari, & Garagiola, 2019).

Tactical decisions concern the design of cross-docking networks. This involves deciding how goods flow through a network that contains more than one cross-docking centre. We refer to the works of Lim, Miao, Rodrigues, and Xu (2005), Chen, Guo, Lim, and Rodrigues (2006), or Ma, Miao, Lim, and Rodrigues (2011) as examples of tactical cross-docking works.

Concerning operational planning, the problems at this level relate to vehicle routing, truck scheduling, door assignment and internal resource scheduling. The vehicle routing problem considers combining distribution policies into the network, e.g., direct shipments or milk runs, by flexibly deciding per supplier whether to stop at a cross-docking terminal. We refer to a review of the VRP literature and a case study for multiple cross-docking terminal routing conducted by Nasiri, Rahbari, Werner, and Karimi (2018). Truck scheduling involves decisions regarding the schedule of what trucks are (un)loaded at which dock doors. The door assignment decisions regard the assignment and service of inbound or outbound destinations to specific dock doors. The types of door policies have been classified as follows: exclusive door assignment based on the destination, assignment based on the type of product (e.g., fresh, cooled storage) or based on the type of truck (Stephan & Boysen, 2011). Moreover, classical practices have commonly addressed exclusive door services, where typically inbound trucks can only dock on one side of the terminal and the outbound trucks on the opposite side. A flexible approach of mixed service doors allows both inbound and outbound trucks to be docked at any door. A recent example of research on mixed service doors with promising results has been conducted by Bodnar et al. (2017). Lastly, internal resource scheduling relates to decisions regarding the multiple resource coordination problems in the (un)loading, scanning, transhipment, consolidation and possible value-adding processes inside the terminal. For an example of research on workforce planning integration with internal transport planning for (un) loading, we refer to the work of Tadumadze, Boysen, Emde, and Weidinger (2019). Considering the rich family of cross-docking problems based on the planning level, in this chapter, we limit the collection of cross-docking related works to those addressing internal resource and truck scheduling operations. Regarding the latter, the first classification of truck scheduling is provided by Boysen and Fliedner (2010). Since then, the naming of the various types of truck scheduling in the related literature is found to be inconsistent, where different terms refer to the same type of problem or a general one such as cross-docking scheduling when referring to a specific type of cross-docking scheduling problem (Ladier & Alpan, 2016). Consequently, we use the classification provided by Ladier and Alpan (2016):

- Truck-to-door assignment: It aims at determining which door each truck is assigned to. Truck-to-door problems are scheduling problems where time is explicitly considered.
- Truck-to-door sequencing: This type of cross-docking problem considers the order of trucks and their assignment to doors to minimize the average distance the cargo is transported inside the terminal.
- Truck-to-door sequencing and scheduling: These problems focus on the temporal dimension and do not consider which door each truck is assigned to as long as the maximum number of doors is not exceeded. The distinction between both problems is that sequencing only involves the order in which the trucks are processed, while scheduling explicitly considers the arrival/departure times.

For a more in-depth nuance between the types of truck scheduling, the reader is referred to the work of Ladier and Alpan (2016). Moreover, each of the aforementioned problems is dependent on one another in some way, and it is possible to create various syntheses of various levels of decision-making per unique industry. Extensive research has been done on the synchronization of the different decision levels (Buijs et al., 2014; Enderer et al., 2017; Luo, Yang, & Wang, 2019).

Industry 4.0 Components in Manufacturing and Logistics

In this section, we introduce the general concept of Industry 4.0 and list its different components relevant to cross-docking. After an extensive literature search and classification, Nazarov and Klarin (2020) define Industry 4.0 as 'the integration of networking capabilities to machines and devices that allows seamless collaboration between the digital and the physical ecosystems for increased efficiencies in the organizational value chains that transform industries and the society for an increased level of productivity and efficiency'. Wagire, Rathore, and Jain (2020) conduct a systematic review and construct a taxonomy of Industry 4.0 research. They found 13 distinct research themes that are clustered in a taxonomy of five principal research areas: Industry 4.0 realization strategies, standards and reference architectures, smart factories, real-time data management and new business models. Ivanov, Tang, Dolgui, Battini, and Das (2021) conducted surveys among researchers to examine the current standing of Industry 4.0 research in Operations Management. They found the following technological aspects of Industry 4.0 in Operations Management: (1) cyber-physical systems/embedded systems, (2) Internet of Things (IoT), (3) 3D printing/additive manufacturing, (4) automated guided vehicles, (5) mobile robots, (6) augmented reality, (7) big data and analytics, (8) artificial intelligence, (9) track-and-trace systems, (10) machine-to-machine communication, (11) cloud services, (12) smart products, (13) blockchain and (14) RFID. The systematic literature reviews in Hofmann and Rüsch (2017) and Garay-Rondero, Martínez-Flores, Smith, Morales, and Aldrette-Malacara (2019) recognize the same Industry 4.0 technology components in (digital) supply chain management and logistics research. Based on the aforementioned surveys and literature review, we synthesize the technological components of Industry 4.0 that are potentially relevant to cross-docking, as summarized in Table 1.

Cyber-physical systems integrate computation with physical processes (Lee & Seshia, 2011). It integrates computing, communication, and storage with monitoring and control of entities in the physical world (Sha, Gopalakrishnan, Liu, & Wang, 2008). Inside these cyber-physical systems, a network of machines can be connected using the IoT, which is a concept that entails the connectivity of machines (e.g., 3D printers and AGVs), smart

Table 1. Synthesis of Industry 4.0 Technological Components for Cross-Docking.

Industry 4.0 Technology for Cross-Docking	Description
Cyber-physical systems/embedded systems	Integration of physical processes and computation
Internet of things/distributed control	Connectivity of machines via the internet
AGVs/mobile robots	Automated movement or transportation on a pre-defined path
Artificial intelligence/big data and analytics	The use of modern computing for better analysis and decision-making
Track-and-trace systems/RFID/smart sensors	Tracking of physical entities using sensors
Machine-to-machine communication/ networked automation	Direct communication between automated machines

Source: Based on Hofmann and Rüsch (2017), Garay-Rondero et al. (2019), and Ivanov et al. (2021).

sensors, software (e.g., artificial intelligence algorithms for decision-making) and other embedded systems (Kumar, Tiwari, & Zymbler, 2019). Examples of (potential) adoption of Industry 4.0 in manufacturing and logistics are: (1) the full connectivity of suppliers, (2) logistics and suppliers in a single platform, (3) position-based routing of interconnected vehicles to prevent congestion, (4) fill-level information directly communicated to suppliers using smart sensors, (5) full control of a supply chain using RFID sensors (Hofmann & Rüsch, 2017) and (6) the use of sensors to predict maintenance of manufacturing machines (Lee, Bagheri, & Kao, 2015). In this systematic literature review, we examine the adoption of Industry 4.0 topics (Table 1) in scientific studies about cross-docking.

METHODOLOGY

To find out what cross-docking models have been implemented into practice over the recent five years, we conduct a systematic literature review on studies testing and applying quantitative approaches to cross-docking operational decision levels. This study differs from other recent review studies in the cross-docking domain by explicitly focussing on papers that consider industry practice, e.g., a practical case or incorporating real-world data. The purpose of the study is to extend the comparison framework between industry practices and optimization literature from Ladier and Alpan (2016), with a focus on real-world settings. In addition, we study the degree to which Industry 4.0 concepts have been adopted in research and practice.

As indicated in Kitchenham and Charters (2007), we develop a review protocol to guide the identification, selection and extraction process of collected studies. In doing so, we followed the guidelines within the PRISMA method (Moher, Liberati, Tetzlaff, Altman, & The PRISMA Group, 2009) and also considering the COCHRANE handbook (Higgins et al., 2019). For our systematic literature review, five phases are formulated: (1) definition of the review scope and formulation of review questions, (2) determination of search terms, (3) formulation of exclusion and inclusion criteria, (4) analysis and (5) synthesis of findings. In Section 'Phase 1: Scope and Review Questions', the review questions are explained. Next, in Section 'Phase 2: Search Terms', we elaborate on the search terms and finally, we detail the inclusion and exclusion criteria in Section 'Phase 3: Inclusion and Exclusion Criteria'.

Phase 1: Scope and Review Questions

To systematically assess the eligibility of each paper for inclusion, we formulate review questions. First, we address the industry practice with the review question: 'To what extent does the paper consider industry practice?' Next, we consider the level of decision-making that is considered (i.e., strategic, tactical or operational) with the question: 'What planning level is the work at hand addressing?' The solution method proposed is investigated using the review question: 'What solution method is proposed?' Finally, we consider the three questions related to the type of information that needs to be extracted after inclusion: 'What are the performance indicators utilized?', 'What were the cross-docking settings utilized in the solution method?' and 'On what data was the solution method tested?'

Phase 2: Search Terms

The online databases considered for this study were *Scopus* and *Web of Science*. Only reports written in English are eligible for inclusion. The considered timeframe for publications is from 2015 to May 2020, and all source types are eligible for inclusion. After piloting several search queries, we settle on the terms '*cross-dock**' *OR* '*crossdock**' *OR* '*cross dock**'. These conditions result in 704 studies. At first glance, we find a significant number of publications in the search pool on a biochemical process by the name of cross-docking, a binding mechanism for receptors of proteins and ligands. The selection is then filtered to exclude all the research from the biochemistry domain on the cross-docking process using the search term *AND NOT* ('*ligand**' *OR* '*protein**'), which reduces the number of studies from 704 to 536. We compare the occurrence of cross-docking keywords of the search pool before and after the search exclusion and find that the number of hits on cross-docking specific keywords (e.g., trucks and logistics) remains unchanged, i.e., no literature is mistakenly excluded. The mentioned search criteria are illustrated in Table 2. After duplication removal, 337 records remain for the screening phase.

Phase 3: Inclusion and Exclusion Criteria

To enhance the reproducibility and robustness of our review, we formulate and present the protocol for including studies in the final selection (Denyer & Tranfield, 2009; Higgins et al., 2019). We first screen the title, abstract and keywords, and in a second phase we read all full papers. After the first screening phase, 55 studies of 337 remain for in-depth screening. Table 3 shows the inclusion and exclusion criteria used.

After the first phase, we read all papers and use the same criteria for exclusion. Specific focus lies on the industry practice that is considered. We exclude a paper when it does not have a case study, on-site study, real-world comparison or real-world data. We also exclude papers that do not use a quantitative solution approach or do not target an

Table 2. Search Criteria used in this Systematic Literature Review.

Search terms for titles, abstracts and keywords	('cross-dock*' OR 'crossdock*' OR 'cross dock*')
Filter	AND NOT ('ligand*' OR 'protein*')
Timeframe	Jan 2015–May 2020
Language	English
Source type	All
Document type	All
Publication status	All

Table 3. Criteria for Inclusion and Exclusion.

Inclusion Criteria	Exclusion Criteria
Practical case presented	Theoretical case without real data
Quantitative solution method	The cross-docking concept is not the main object of study
Targets truck scheduling or internal resource operational decision levels	Domain level too wide
Published between 2015 and May 2020	Duplicate studies
	Non-English written papers

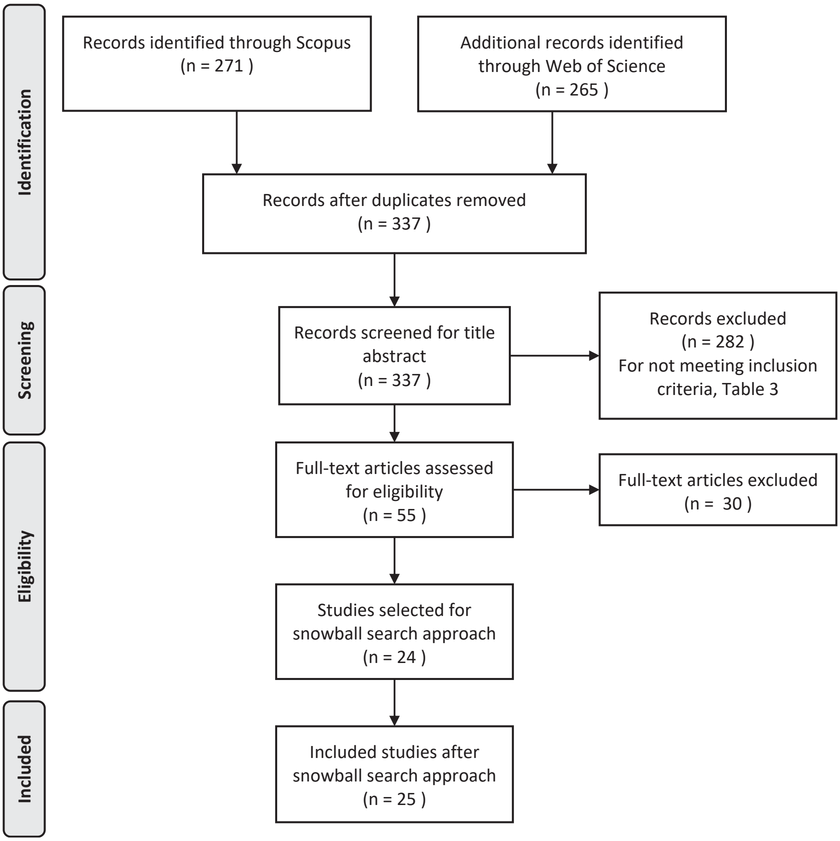


Fig. 3. PRISMA Flow Diagram. *Source:* Adapted from Moher et al. (2009).

operational cross-docking problem. After screening the 55 remaining studies, 25 studies remain in the selection.

The outcome of the systematic literature review is summarized in the PRISMA flow diagram in Fig. 3. The final number of selected studies is 25, obtained from the initial 337 records.

Descriptive and thematic features are extracted from the selected records. The studies are thematically classified by answering the review questions. Table 4 highlights how descriptive and thematic information is extracted.

RESULTS

In this section, the result of the systematic literature review is presented. First, a general overview of the literature is given in Section 'General Overview of Cross-Docking Literature'. Next, in Section 'Solution Methods and Industry 4.0 Adoption in the

Table 4. Classification Categories Used to Extract and Classify Collected Works.

Category	Information
Year	Year of publication
Country	Author's country of affiliation
Type of document	Conference paper, journal article, dissertation
Real-world cross-docking setting	Company industry, country, data source, implementation period and the cross-docking setting concepts
Decision-making level	What cross-docking problem was addressed?
Solution method	Exact method, (meta-)heuristic or simulation
Performance measures	Which performance measures were utilized?
Industry 4.0	Mentioning of Industry 4.0, use of Industry 4.0 concepts in the solution approach
Findings	Results of the model, relevant findings and future research directions

Cross-Docking Literature', we discuss considered problems, solution approaches and Industry 4.0 aspects of cross-docking. In Section 'Cross-Docking Characteristics', we discuss the cross-docking characteristics and in Section 'Performance Indicators' the used performance indicators.

General Overview of Cross-Docking Literature

The selection of papers includes 17 journal papers and 8 conference papers. Table 5 provides an overview of the source of data for the industry case studies as well as the country and industry at which the case company operates. Fig. 4 summarizes the different industries in which the considered companies are active. Cross-docking seems most popular among retail companies, the automotive industry and logistics companies.

Two papers explicitly share the results of an implementation phase of their model. Aulin et al. (2020) were allowed eight days to record data for variable sensitivity analyses (e.g., on the number of workers engaged and product flow). Furthermore, the research at Renault reported by Serrano, Delorme, and Dolgui (2015) for cross-docking internal operation planning was followed up with an 8-week implementation of a simplified version of the developed solution method. To shed light on the interaction between the company and the researchers, we classify the origin of the model data. 'Company data' in Table 5 stands for receiving data from the company operations, or product demand and supply, as well as the type of utilized equipment. When measurements or on-site observations are explicitly mentioned, the paper is denoted by 'Measured data'. Chargui, Bekrar, Reghioui, and Trentesaux (2018) and Chargui, Bekrar, Reghioui, and Trentesaux (2019b) are both an extension of Chargui, Reghioui, Bekrar, and Trentesaux (2016). In the latter case, a practical partner is mentioned as the source of data. However, the researchers explicitly state the test data are inspired by a case and not on a partition of company data. An example of both utilizing company data and measured data is Zenker and Boysen (2018). They received the fixed departure schedules of a postal service provider and historical data on the order inflow rate. Furthermore, in an on-site visit, the internal layout and operation were documented and used as constraints in the model.

Table 5. Classification of Selected Studies Concerning Real-World Settings.

	Real-World Setting		
	Data Source	Country	Industry
Aulin et al. (2020)	Measured data	Ukraine	Logistics
Azimi (2015)	Company data	Iran	Shipping port
Benbitour, Sahin, and Barbieri (2016)	Company data	France	Automotive
Benrqya (2019)	Measured data	France	Retail (FMCG)
Bodnar et al. (2017)	Company data, generated data	The Netherlands	Retail
Buijs et al. (2016)	Company data	The Netherlands	Retail (supermarket)
Chargui et al. (2018)	Generated inspired by case	ns	Retail (household products)
Chargui et al. (2019b)	Generated inspired by case	ns	Retail (household products)
Coindreau, Gallay, Zufferey, and Laporte (2019)	Company data	ns	Automotive
Fanti, Stecco, and Ukovich (2016)[L]	Company data	Italy	Textile
Fathollahi-Fard et al. (2019)	Company data	Iran	Shipping port
Horta, Coelho, and Relvas (2016)	Company data	Portugal	Retail (fruits and vegetables)
Jarrah, Qi, and Bard (2016)[L]	Company data	USA	Postal services
Khannan, Nafisah, and Palupi (2018)	Company data, measured data	Indonesia	Textile
Khorshidian, Akbarpour Shirazi, and Fatemi Ghomi (2019)	Company data	Iran	Food
Luo et al. (2019)	Company data, measured data	China	Paint
Nasiri et al. (2018)	Company data, generated data	Iran	Logistics
Pawlewski and Hoffa (2014)	Company data	ns	Logistics
Piao and Yao (2017)	Company data	China	Retail
Rijal, Bijvank, and de Koster (2019)	Company data	The Netherlands	Retail (supermarket)
Serrano et al. (2015)	Company data	ns	Automotive
Serrano, Delorme, and Dolgui (2017)	Company data	ns	Automotive
Serrano, Moral, Delorme, and Dolgui (2016)	Company data	ns	Automotive
Yu, Yu, Xu, Zhong, and Huang (2020)	Company data	ns	E-commerce logistics
Zenker and Boysen (2018)	Company data, measured data	Germany	Postal services

Note: Studies denoted with an 'L' are found in the state-of-the-art analysis of Ladier and Alpan (2016).

Solution Methods and Industry 4.0 Adoption in the Cross-Docking Literature

The outcome of the classification of the quantitative solution methods and the associated cross-docking problems is presented in Table 6. Here we distinguish between exact, heuristic, meta-heuristic and simulation methods. We observe that most research applies exact models to cross-docking problems. In addition, some different types of heuristics and metaheuristics are used. Some authors use simulation to validate their results. Research primarily considers internal resource operations or the truck-to-door scheduling problem.

Next, we study the 25 papers on Industry 4.0 related features. After studying the literature on Industry 4.0 in logistics in general (see Section 'Industry 4.0 Components in

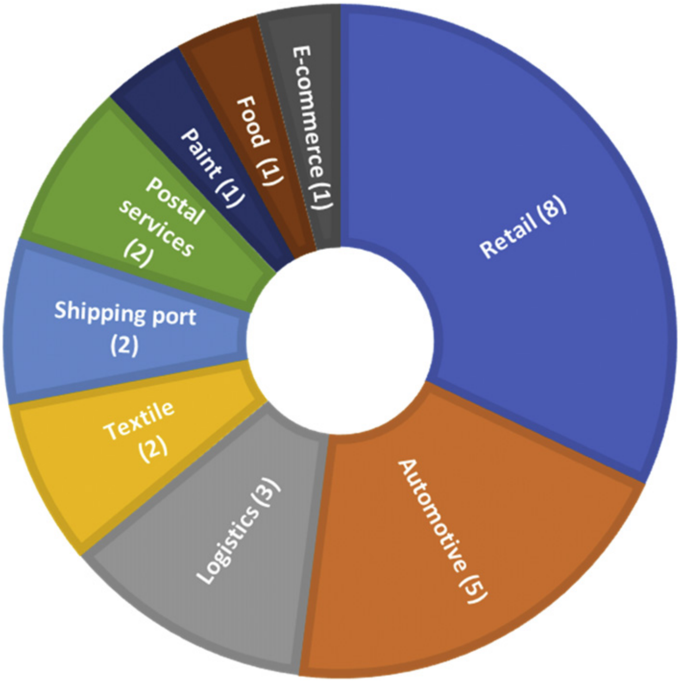


Fig. 4. Frequency of Industries of Practical Cases. The Number of Related Works Is Indicated in Parentheses.

Manufacturing and Logistics'), we defined several technological components related to Industry 4.0. These categories are cyber-physical systems, IoT, AGVs, artificial intelligence, smart sensors, and machine-to-machine communication (see Table 1). Only 7 out of 25 papers discuss one or more of these Industry 4.0 related components (see Table 6).

We consider networked automation, e.g., AGVs and robots that communicate to perform tasks, a concept belonging to Industry 4.0. From the seven papers, three consider automated conveyors but do not mention the interconnectivity of machines or networked systems. For an automated conveyor to work, RFID or other sensor technology is needed. In Jarrah et al. (2016), automated conveyors and automated flow through a building are briefly discussed, including the need for a controlling computer system. In Zenker and Boysen (2018), similar concepts are discussed, and the need for recognition technology, e.g., RFID, for automated sorters is discussed.

Of the seven papers, two relate to physical internet hubs (PI-hubs), namely Chargui et al. (2018) and Chargui et al. (2019b). Both papers consider PI applied to cross-docking hubs. The term 'physical internet' was introduced by Benoit Montreuil and considers the way physical objects are transported, handled, stored, supplied, realized and used (Montreuil, 2011). In the PI, in analogy with the digital internet, shipments will be transported through a network optimally utilizing various transport modalities and transfer hubs, where shipments are possibly decomposed into multiple packages, but eventually, all arrive at their destination upon agreed delivery time, without the sender needing to worry about how its shipment gets there. The PI '(…) combines standardized, modular and intelligent containers with new logistics protocols and business models, resulting in a collaborative,

Table 6. Classification of Selected Studies on Solution Method Approaches Utilized in the Study.

	Cross-Docking Problem	Solution Method Approaches			
		Method	Description	Simulation	Industry 4.0 Components
Aulin et al. (2020)	Internal resources operation	Tailored method	Multiple linear regression		
Azimi (2015)	Truck-to-door assignment, internal resource operation	Meta-heuristic	Genetic algorithm	X	
Benbitour et al. (2016)	Internal resource operations	–		X	
Benrqya (2019)	Internal resource operations	Exact	Cost model		
Bodnar et al. (2017)	Truck-to-door scheduling	Exact, meta-heuristic	Mixed-integer linear programming (MILP), adaptive large neighborhood search		
Buijs et al. (2016)	Truck-to-door sequencing, vehicle routing, internal resource operations	–		X	
Chargui et al. (2018)	Internal resource operations	–		X	Cyber-physical systems, IoT, M2M
Chargui et al. (2019b)	Truck-to-door scheduling, internal resource operations	Heuristic, meta-heuristic	Scheduling heuristic, tabu search		Cyber-physical systems, IoT, M2M
Coindreau et al. (2019)	Internal resource operations	Exact, heuristic	MILP, decomposition heuristic		
Fanti et al. (2016)[L]	Internal resource operations	Exact, heuristic	MILP		RFID
Fathollahi-Fard et al. (2019)	Truck-to-door sequencing	Exact, meta-heuristic	MILP, social engineering optimization adaptations		RFID
Horta et al. (2016)	Internal resource operations	Exact	MILP		
Jarrah et al. (2016)[L]	Truck-to-door scheduling, internal resource operations	Exact, tailored method	MILP, three-step approach		
Khannan et al. (2018)	Internal resource operations	Exact	MILP		
Khorshidian et al. (2019)	Truck-to-door scheduling, vehicle routing	Exact, tailored method	Bi-objective MILP, 3POM		

Luo et al. (2019)	Internal resources operations	Exact, meta-heuristic	MILP, hybrid genetic algorithm with local search and opposition-based learning		
Nasiri et al. (2018)	Truck-to-door-scheduling, vehicle routing, supplier and cross-docking selection, internal resource operations	Exact, tailored method	MILP; TSSA		RFID, cyber-physical systems
Pawlewski and Hoffa (2014)	Truck-to-door assignment problem	–	–	X	
Piao and Yao (2017)	Internal resource operations	–	–	X	
Rijal et al. (2019)	Truck-to-door scheduling	Exact, Metaheuristic	MILP, adaptive large neighborhood search		
Serrano et al. (2015)	Internal resource operation, distribution planning	Exact	MILP		
Serrano et al. (2016)	Truck-to-door scheduling, Internal resource operations	Exact	MILP		
Serrano et al. (2017)	Truck-to-door scheduling, Internal resource operations	Exact	MILP		
Yu et al. (2020)	Truck-to-door scheduling, Internal resource operations	Exact	MILP		RFID
Zenker and Boysen (2018)	Truck-to-door scheduling, internal resource operations	Exact, heuristics, meta-heuristic	MILP, greedy, fix-and-optimize, tabu search		RFID

Note: Studies denoted with an ‘L’ are found in the state-of-the-art analysis of Ladier and Alpan (2016).

highly distributed and leveraged logistics and distribution system' (Montreuil, Meller, & Ballot, 2010).

Transfer hubs play a crucial role within the PI, highlighting the importance of cross-docking operations. The PI exhibits multiple Industry 4.0 characteristics, e.g., cyber-physical systems, IoT, AGVs, track-and-trace systems, smart sensors, and machine-to-machine communication. In Chargui et al. (2018), the PI objects are called 'PI-containers', 'PI-movers' and 'PI-nodes'. PI-containers are modular and smart containers that can cope with different dimensions and weights, as decided by the system. PI-movers can be trucks, wagons, conveyors or lifts that are linked to the PI system. Finally, PI-nodes are locations where cross-docking operations are conducted on materials, e.g., assembly, picking, routing or monitoring. Chargui et al. (2018) show that PI cross-docking hubs (PI-hubs) that are fully automatic outperform manual cross-docking hubs regarding waiting times of inbound and outbound trucks, the total time a product spends in the cross-dock and the number of trucks waiting. Chargui et al. (2019b) conduct a robustness test under different internal resource breakdown disruptions for classical cross-docking systems, as well as for PI-hubs. They show the potential weakness of interdependence of machines in a PI-hub. Although it is likely that the PI increases efficiency and reduces costs, it may be more sensitive to machine failures compared to classical cross-docking systems (Chargui et al., 2019b).

Cross-Docking Characteristics

We classify the papers into the various characteristics of cross-docking settings in Table 7. From it, we can indicate that most of the case studies investigate a manual internal transportation mode, five consider an automatic mode and two consider a combined mode of transport.

For the door service mode, we find that most of the researchers design the door policy with an exclusive door service, one proposes a mixed service mode and three propose a combined door service mode. In an exclusive mode, each door is dedicated to receiving inbound or outbound trucks exclusively. A mixed mode is in place when a door may handle both inbound and outbound trucks. The combined mode is when some doors utilize mixed service while other doors have an exclusive service mode. None of the studies allows preemption to occur in the planning schedules. Preemption allows interruption of (un) loading of trucks, i.e., another truck is processed instead of the interrupted truck, which is parked to continue the (un)loading process later.

The temporary storage capacity determines if and how many goods can be stored temporarily. When the outbound truck is not present when a product is unloaded, the product must be moved to the storage area temporarily. This storage area has limited storage capacity when space is scarce within a terminal. If a terminal is large, the temporary storage capacity is often modelled as infinite. In some industries, temporary storage is not viable, e.g., frozen or perishable goods, in which case temporary storage capacity is considered to be zero. For temporary storage capacity, we find 10 records that allow unlimited storage capacity for the modelling constraints, 2 do not allow temporary storage at all (zero) and the remaining 13 studies implement a temporary storage capacity constraint.

Internal resource capacity describes the handling capacity of the internal transportation mode, which may either be limited or unlimited. For automatic modes, it considers the capacity of the conveyor belt network, and for manual modes of transportation, it considers, for instance, the maximum number of workers or forklifts. For internal resource

Table 7. Classification of Cross-Docking Characteristics.

	Strategic	Tactical Level Planning				Operational Level Planning	
	Internal Transport Method	Service Mode	Preemption	Temporary Storage Capacity	Internal Resource Capacity	Arrival Time Pattern	Departure Time Constraints
Aulin et al. (2020)	Manual	Exclusive	No	Limited	Limited	Per truck	No
Azimi (2015)	Manual	Combined	No	Limited	Limited	Per truck	No
Benbitour et al. (2016)	Manual	Exclusive	No	Limited	Limited	Per truck	No
Benrqya (2019)	ns	Exclusive	No	Limited	∞	Per truck	No
Bodnar et al. (2017)	Manual	Combined	No	∞	∞	Per truck	Outbound
Buijs et al. (2016)	Manual	Mixed	No	0	Limited	Per truck	Both
Chargui et al. (2018)	*	Exclusive	No	Limited	Limited	Per truck	No
Chargui et al. (2019b)	*	Exclusive	No	Limited	Limited	Per truck	No
Coindreau et al. (2019)	Manual	Exclusive	No	∞	∞	Per truck	No
Fanti et al. (2016)[L]	Combined	Exclusive	No	0	∞	Zero	No
Fathollahi-Fard et al. (2019)	Automatic	Exclusive	No	∞	∞	Zero	No
Horta et al. (2016)	Manual	Combined	No	Limited	∞	Zero	No
Jarrah et al. (2016)[L]	Automatic	Exclusive	No	∞	Limited	Per truck	Outbound
Khannan et al. (2018)	Manual	Exclusive	No	Limited	∞	Per truck	No
Khorshidian et al. (2019)	Manual	Exclusive	No	∞	∞	Per truck	Both
Luo et al. (2019)	Manual	Exclusive	No	∞	∞	Zero	No
Nasiri et al. (2018)	Manual	Exclusive	No	∞	∞	Zero	Both
Pawlewski and Hoffa (2014)	Manual	Exclusive	No	∞	Limited	Zero	No
Piao and Yao (2017)	Manual	Exclusive	No	∞	Limited	Zero	No
Rijal et al. (2019)	Manual	Combined	No	Limited	∞	Per truck	Outbound
Serrano et al. (2015)	Manual	Exclusive	No	Limited	Limited	Per truck	No
Serrano et al. (2016)	Manual	Exclusive	No	Limited	Limited	Zero	No
Serrano et al. (2017)	Manual	Exclusive	No	Limited	Limited	Per truck	No
Yu et al. (2020)	Automatic	Exclusive	No	∞	∞	Zero	No
Zenker and Boysen (2018)	Combined	Exclusive	No	Limited	Limited	Per truck	Outbound

Notes: The * sign indicates dual modes; Studies denoted with an 'L' are found in the state-of-the-art analysis of Ladier and Alpan (2016).

capacity, we find a nearly equal distribution of use of internal resource capacity, with 13 records including a constraint on internal resources, e.g., the number of workers or equipment, and the remaining 12 studies not including such constraints.

Concerning the arrival pattern, the majority (16 out of the 25) consider a scattered arrival pattern per truck, and in the other nine records, it is assumed that all trucks are available from the beginning of the planning period. If the arrival of trucks is concentrated and the unloading is non-restrictive, then it is assumed that times are defined per truck. This feature applies to both inbound and outbound trucks. Moreover, we find that over half of the studies assume no constraints on truck departure, e.g., no other appointment deadline earlier or further ahead in the distribution network for inbound or outbound trucks. Moreover, we observe that four studies assume deadlines on both inbound and outbound trucks, five include departure deadlines on outbound trucks exclusively and no study imposes deadlines on inbound trucks exclusively.

Performance Indicators

Table 8 shows the performance indicators used in the selected papers. In the last column, all performance indicators not included by Ladier and Alpan (2016) are displayed. These performance measures are included to illustrate whether novel indicators have gained popularity over the past five years. For instance, among the selection, there are multiple papers with internal resource performance indicators: internal resource utilization and storage surface area.

The most prominent performance measures among the studies are inventory level (total number of products stocked), truck processing time deviation (finishing (un)loading earlier or later than planned), makespan (the difference between the start of the first operation and the last operation, e.g., the last truck's dispatch) and distance travelled, i.e., the distance travelled within the terminal from door to door. The next most frequent performance measure is balanced workload, which is the fair distribution of workload among workers according to skills and capacity. Furthermore, we observe several performance measures that remain unutilized: working hours, number of touches (the average number of touches is an indicator of employee costs), unloading time and preemption cost. On the other hand, all other performance measures are only utilized by either one or two studies, e.g., congestion, which is caused by high traffic in certain areas of the building, delaying all processes, total product stay time, which is the total time a product spends in the cross-docking terminal, loading time, door utilization, which is linked to the efficiency of the (un)loading and the number of doors in use at a cross-dock, and products not loaded, i.e., missed orders.

From the collected information in this and previous subsections, cross-docking characteristics and performance measures have been provided. In the next sections, they are used as comparison components to analyze and discuss their contributions while also providing insights in the light of Industry 4.0.

DISCUSSION

In this section, we discuss the outcomes of our systematic literature review and we compare them with the findings of the state-of-the-art review conducted by Ladier and Alpan (2016). In doing so, we identify studies from 2015 to 2020 on the subset of cross-docking operational problems that consider a practical case, and we classify each paper according

Table 8. Performance Measures in Cross-Docking Literature.

	Performance Measures														
	Inventory Level	Working Hours	Distance Travelled	Congestion	Total Product Stay Time	Number of Touches	Truck Processing Deviation	Loading Time	Unloading Time	Door Utilization	Products Not Loaded	Makespan	Preemption Cost	Balanced Workload	Other Performance Measures
Aulin et al. (2020)				X										X	–
Azimi (2015)															Fleet size, internal resources utilization
Benbitour et al. (2016)			X												Storage surface area, number of picking train journeys
Benrqya (2019)	X														Supply chain cost
Bodnar et al. (2017)	X						X								–
Buijs et al. (2016)			X	X	X						X	X			Workers on site
Chargui et al. (2018)							X					X			Waiting time, number of trucks waiting, internal resource utilization
Chargui et al. (2019b)							X								–
Coindreau et al. (2019)	X													X	–
Fanti et al. (2016)[L]												X			–
Fathollahi-Fard et al. (2019)												X			–
Horta et al. (2016)			X												–

Table 8. *(Continued)*

	Performance Measures														
	Inventory Level	Working Hours	Distance Travelled	Congestion	Total Product Stay Time	Number of Touches	Truck Processing Deviation	Loading Time	Unloading Time	Door Utilization	Products Not Loaded	Makespan	Preemption Cost	Balanced Workload	Other Performance Measures
Jarrah et al. (2016)ᴸ										X				X	Number of changes in door-destination assignment, number of workers, loader utilization
Khannan et al. (2018)			X												Storage space
Khorshidian et al. (2019)							X	X				X			Risk aversion, product participation
Luo et al. (2019)								X				X			Order simultaneity
Nasiri et al. (2018)	X						X								Purchasing cost, waiting times
Pawlewski and Hoffa (2014)			X												–
Piao and Yao (2017)												X			Utilization of internal resources
Rijal et al. (2019)	X		X				X								–
Serrano et al. (2015)	X													X	Inbound/outbound transportation costs
Serrano et al. (2016)	X														Number of outbound trucks
Serrano et al. (2017)							X							X	–
Yu et al. (2020)	X						X								Longest waiting time, asynchronized operation penalty
Zenker and Boysen (2018)	X														–

Note: Studies denoted with an 'L' are found in the state-of-the-art analysis of Ladier and Alpan (2016).

to the elements of the comparison framework with industry practices according to Ladier and Alpan (2016) considering papers up to 2015. From them, we discuss the cross-docking characteristics, the implications for Industry 4.0 adoption and the used performance indicators.

Cross-Docking Characteristics and Industry 4.0 Adoption

We observe that 19 articles in our review assume a manual mode of internal transportation, 5 assume an automatic mode and only 2 propose a combined transportation mode. Two papers are counted to both manual and automatic as they compare the manual mode with an automated PI mode for the same industrial case inflow data (Chargui et al., 2018, 2019b), and for one study the mode of transport is not specified. Our observations indicate that the occurrence rates for internal transportation mode assumptions are similar to the occurrence rates in the state-of-the-art models before 2015, but with a higher share of the combined mode of transport. Completely automated systems are rare in the industry. Ladier and Alpan (2016) argue that this is because of the advantages in the flexibility of manual labour, even though automated systems may prove more efficient in some cases. However, it may be expensive to expand the capacity of automated systems to cover for fluctuations in demand. Combined modes of internal transport are therefore more common in industry than fully automatic systems. Automatic systems have been shown to outperform manual transportation in specific areas; however, fluctuations and uncertainty have a larger negative effect compared to classical systems. Future research can investigate strategies for combined modes of transport in different configurations.

Both the mixed-mode door service (i.e., a door may be for both inbound and outbound trucks) and exclusive door service types were found to be frequently occurring in practice, while a combined mode (i.e., mixed-mode combined with exclusive mode) was perceived as non-suitable by research and managers (Ladier & Alpan, 2016). The state-of-the-art research uses exclusive door service modes more than the mixed modes before 2015. Ladier and Alpan (2016) recommended more research to also test their solution approaches with the mixed service mode, as its occurrence in practice is non-negligible. We find similar occurrence rates in the literature from 2015 to 2020, in which an occurrence rate of the exclusive mode assumption on a nearly equal level and even less frequent utilization of the mixed service mode. Hence, this indicates that research has not yet increased the utilization of the mixed door service mode. Only Buijs et al. (2016) propose a mixed service policy for their practical case. They find a reduction of the internal travel distance by 40%, less congestion and other considerable cost savings from their proposed mixed service doors, in combination with other strategic policy changes. The remainder of the studies we found considered a combined mode of door service, which is in contrast with the findings from the preceding review. Bodnar et al. (2017) show that adding a few mixed service doors results in reducing the overall costs of the operation, compared to an exclusive mode of service. Our findings indicate that the gap in addressing the mixed service doors in literature has not been bridged by the contemporary publications that consider practical cases. Additionally, we observe a rise in popularity for combined modes of door service, even though several managers perceive this mode as not suitable. If researchers foresee that implementing a combined mode brings substantial benefits, we recommend to justify the benefits quantitatively and illustrate how the expected miscommunication can be overcome.

Ladier and Alpan (2016) reports preemption to be redundant for managers of cross-docking operations. Moreover, merely 9% of their state-of-the-art papers allow preemption in the model. None of the papers in our study allows preemption in their model, which indicates that researchers share a similar sentiment toward the benefit of preemption.

Cross-docking managers have to deal with capacity constraints. The on-sight survey by Ladier and Alpan (2016) supports this statement, as all managers interviewed dealt with resource limitations, and only one manager experienced a storage capacity significantly large to be considered infinite. However, they find that only 3% of the papers include capacity constraints. Within the publications of the last five years, more studies include capacity constraints: 9 out of 25 studies incorporate both a limited capacity for storage and limited internal resources. The rise in occurrences of limited capacity constraints could be explained due to the scope of the review, by exclusively considering practical cases. The selected studies often receive real data on constraints first-hand or were allowed to evaluate the practical settings on-site. This possibly resulted in a more representable model of practical industry capacity constraints.

Although there is an increase in the use of capacity constraints in current research on practical cases, we nevertheless observe that the gap for utilization of capacity constraints has not yet been fully narrowed.

The arrival time of inbound trucks is subject to the industry and product types and is typically either concentrated around certain periods or spread out over the day. It seems that the retail industry typically works under scattered arrival time patterns (listed as '/truck' in Fig. 5) because we find that six out of the eight studies that examine a practical retail case utilize this assumption. Additionally, we observe an indication that automotive industries tend to operate under scattered arrival patterns, as for four out of the five automotive cases, scattered arrival time is assumed by the researchers. With our findings, we want to highlight the importance of the development of customized cross-docking operational models for specific industries. We recommend continuing to address both types of constraints.

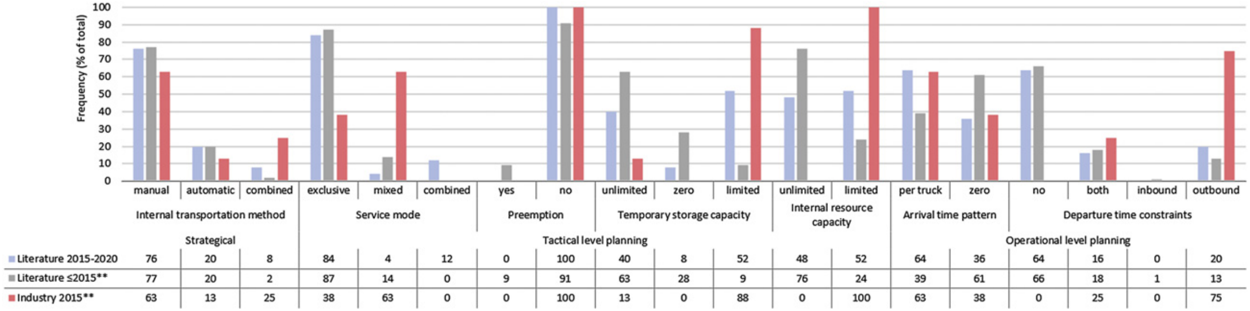
Similarly as before 2015, after 2015, the majority of the studies do not assume departure deadlines for the trucks. Ladier and Alpan (2016) found that nearly all industry managers organize themselves around setting and meeting a tight schedule of deadlines, and hence, the authors recommend future research to bridge the gap with the real-world constraints seen in the industry. We find that this gap has not been adequately addressed.

Finally, we observe in our literature review that Industry 4.0 aspects are rarely considered in the cross-docking literature. Most research either concerns the use of RFID technology for automated sorters or the use of cyber-physical systems in PI-hubs. In a sense, it is remarkable, since cross-docking forms the core of the PI (to enable the transfer of PI-containers at PI-hubs) and Industry 4.0 technologies are required for the PI (all of those from Table 1). However, we see little evidence for the adoption of Industry 4.0 in cross-docking judging from the included sources.

Performance Indicators

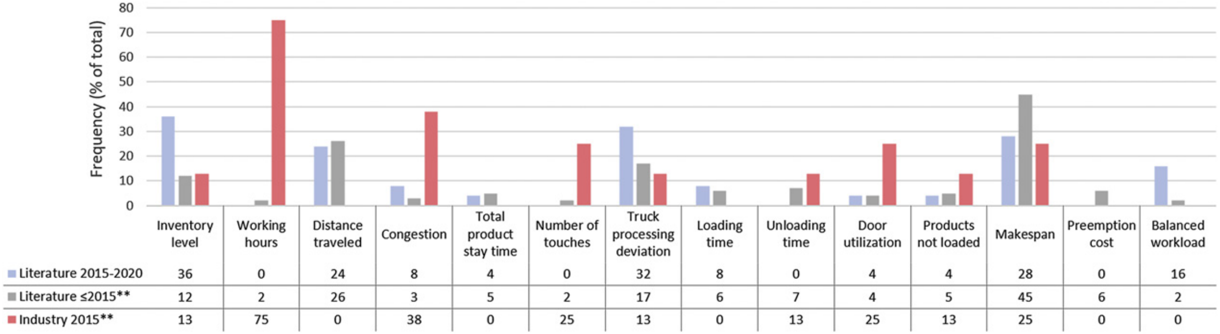
In this section, we discuss the performance indicators extracted from publications that consider a practical case in the last five years, compare our findings to literature before 2015 and provide findings to what was found to be popular for industry practices (secondary findings from Ladier and Alpan (2016)). The occurrence rates are summarized in Figs. 5 and 6.

Risks of congestion are found to gain importance to management as the size of manual internal transportation at cross-docking terminals increased (Ladier & Alpan, 2016).



	Strategical			Tactical level planning										Operational level planning					
	Internal transportation method			Service mode			Preemption		Temporary storage capacity			Internal resource capacity		Arrival time pattern		Departure time constraints			
	manual	automatic	combined	exclusive	mixed	combined	yes	no	unlimited	zero	limited	unlimited	limited	per truck	zero	no	both	inbound	outbound
▆ Literature 2015-2020	76	20	8	84	4	12	0	100	40	8	52	48	52	64	36	64	16	0	20
▆ Literature ≤2015**	77	20	2	87	14	0	9	91	63	28	9	76	24	39	61	66	18	1	13
▆ Industry 2015**	63	13	25	38	63	0	0	100	13	0	88	0	100	63	38	0	25	0	75

Fig. 5. Frequency per Cross-Docking Characteristics Found in Literature From 2015 to 2020, Literature before 2015 and Industry 2015 (**Secondary Data Ladier & Alpan, 2016).



	Inventory level	Working hours	Distance traveled	Congestion	Total product stay time	Number of touches	Truck processing deviation	Loading time	Unloading time	Door utilization	Products not loaded	Makespan	Preemption cost	Balanced workload
Literature 2015-2020	36	0	24	8	4	0	32	8	0	4	4	28	0	16
Literature ≤2015**	12	2	26	3	5	2	17	6	7	4	5	45	6	2
Industry 2015**	13	75	0	38	0	25	13	0	13	25	13	25	0	0

Fig. 6. Frequency per Performance Measure Setting Found in Literature From 2015 to 2020, Literature before 2015 and Industry 2015 (**Secondary Data Ladier & Alpan, 2016).

Concentrated arrival patterns tend to cause more congestion over scattered arrival patterns (Azimi, 2015) since the majority of the trucks need processing at the same time window, which causes the internal transhipment to have high traffic for sorting and preparing the products for dispatch. Thus, balancing the conflict between optimizing internal transport and the risk of congestion is an essential aspect for large manual cross-docking centres, especially for organizations with concentrated arrival times. We notice that congestion is only considered as a performance objective in two papers. Modelling congestion and measuring the costs lacks consensus. However, instead of minimizing congestion, several studies design congestion as a modelling constraint: Buijs et al. (2016) compensate actual movement speed from 2.3 m/s to 1.5 m/s for the material handling team, Bozer and Carlo (2008) restrict adjacent docking of trucks to avoid congestion and Bartholdi and Gue (2000) compensate the waiting time of workers additionally. We recommend future research to formulate constraints to compensate for congestion or to design the scheduling constraints further to avoid congestion as much as possible by default.

We observe some indications that literature might not share the same sentiment of value toward optimizing door utilization and the number of touches. Thus, it might be recommendable to utilize terminology that is common in practice or to justify which and how specific performance objectives improve those currently used in practice. In a few studies that utilize 'per truck' arrival times, there is an additional layer modelled for stochastic or uncertain arrival times (e.g., Azimi, 2015). In practice, arrival times are often outside of the operator's control but could cause delays for unloading other trucks and idle times for workers. Hence, in such cases, the planning model compensates for the scheduling process, e.g., buffer times in between trucks.

Workload forecasting is neglected by the majority of literature in the past (Buijs et al., 2014), even though this is found to be one of the most pressing concerns within the industry (Ladier & Alpan, 2016). We found that nearly every study uses deterministic demand and historical data to evaluate the solution approach. Forecasting customer demand can significantly improve the efficiency across the supply chain, as it facilitates effective upstream make-to-order production strategies and low inventory supply chains (Luo et al., 2019).

The effectiveness of planning under uncertainty can be measured through various sets of performance measures. For instance, potential indicators for uncertainty planning are found to be truck processing deviation, longest waiting time or the number of trucks waiting. In a review of uncertainty factors in cross-docking scheduling and operations, several other performance measures are categorized, and future research directions on uncertainty modelling can be found (Ardakani & Fei, 2020).

Working hours are common cost drivers for operations with manual transportation, and thus it is an important performance indicator for managers of such cross-docking terminals. Nevertheless, we find indications that the primary focus of research is on optimizing the cross-docking operations through other performance indicators since the occurrence rate of working hours as a performance measure is next to none.

Our review results indicate that the majority of literature is geared towards objective functions consisting of inventory level, internal distance travelled, truck processing deviation, makespan, number of workers on-site and internal resources utilization. Certain performance measures directly count toward the number of working hours, e.g., each additional meter travelled internally has to be completed by a worker. On the contrary, optimizing the makespan, i.e., reducing the length of a day of operation, might seem to effectively lead to fewer working hours, while in reality, the first and last truck's arrival is often out of control of management.

Since working hours are a major cost driver for manual cross-docking organizations, we recommend research conducted on manual modes of research to find ways to include working hours or other employee cost objectives in the solution model. An example of an integrated truck and workforce scheduling can be found in Tadumadze et al. (2019).

The state-of-the-art review of literature from before 2015 found that makespan has an occurrence rate of 45% in objective functions for cross-dock scheduling. This initial popularity of makespan for truck scheduling problems can be explained by its success in the general scheduling domain. However, as mentioned previously, makespan in cross-docking is often subject to the arrival of the last inbound truck, which explains why Ladier and Alpan (2016) indicated that makespan was not a primary performance objective for many managers.

We find that, for studies after 2015, there is a higher occurrence rate of the performance measures of truck processing time and inventory levels, compared to the time period preceding 2015.

For truck processing deviation, the time deviation between the scheduled arrival or departure time of trucks and their actual arrival or departure time is minimized. An example can be found in Khorshidian et al. (2019) that presents a new truck scheduling, distribution and portfolio selection model. The model was tested on an industrial case considering six performance measures including truck processing time deviation.

EXTENDED SEARCH ON INDUSTRY 4.0 IN CROSS-DOCKING

In this section, we describe our extended search on Industry 4.0 literature in cross-docking. Apart from the works of Chargui et al. (2018) and Chargui et al. (2019b), we found limited evidence for Industry 4.0 adoption in cross-docking research. This might be caused by the exclusion criteria of our systematic literature review. Since we focussed on practical cases in cross-docking, more theoretical Industry 4.0 research in cross-docking might be excluded. First, we conduct an additional literature search, more focussed on finding the intersection of cross-docking and Industry 4.0. Next, we review the research gaps identified by the literature and discuss the future research directions as identified by our review.

Industry 4.0 Components in Cross-Docking Literature

For this systematic search, opposed to the first review, we include publications from before 2015 and extend our search to more theoretical work. Again we classify the research in different Industry 4.0 sub-topics, as introduced in Section 'Industry 4.0 Components in Manufacturing and Logistics'. The sub-topics are (1) cyber-physical systems, (2) IoT, (3) machine-to-machine communication, (4) AGVs/robotics, (5) artificial intelligence and (6) RFID/smart sensors.

To find keywords related to Industry 4.0, we did a search query with the phrase ('industry 4*' OR 'smart industry'). The top 2000 papers are exported to VOSViewer, which is software used for visualizing scientific subjects (van Eck & Waltman, 2010). See Fig. 7 for an overview of keywords that occur at least 35 times in the 2000 papers.

Based on the bibliometric cloud, we select the following keywords for the new search query: 'Industry 4.0', 'Big Data', 'Cyber physical', 'Internet of Things' and 'Embedded Systems'. We also include the term 'Physical internet', since this is the subject of the only

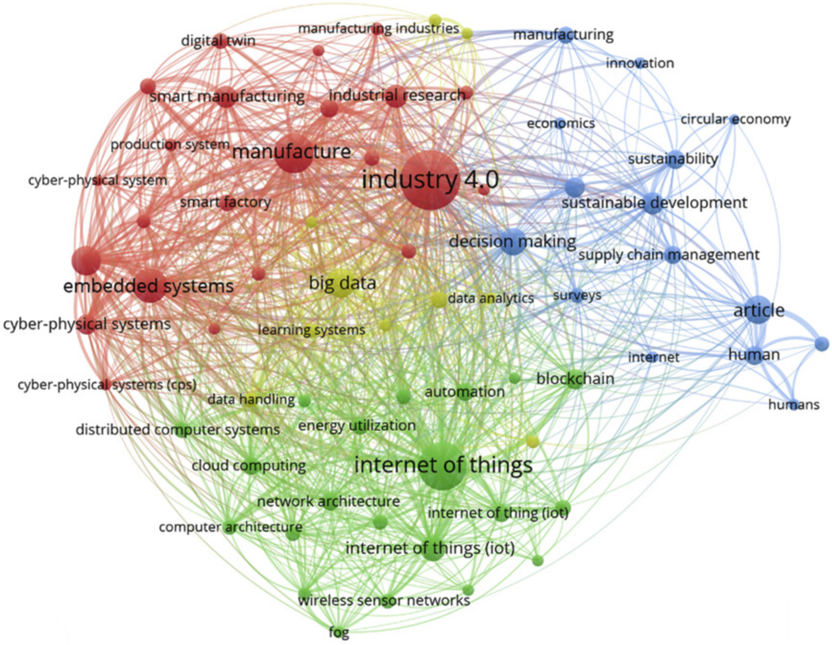


Fig. 7. Bibliometric Network Concerning Industry 4.0.

Table 9. The Search Criteria of the Systematic Literature Review.

Search terms for titles, abstracts and keywords	('cross-dock*' OR 'crossdock*' OR Cross dock*') AND ('industry 4*' OR 'big data' OR 'Cyber physical' OR 'Internet of things' OR 'IOT' OR 'Embedded system*' OR 'Smart industry' OR 'Artificial intelligence' OR 'cloud' OR 'automation' OR 'smart manufacturing' OR 'physical internet')
Filter	AND NOT ('ligand*' OR 'protein*')
Timeframe	1950–May 2020
Language	English
Source type	All
Document type	All
Publication status	All

sources about Industry 4.0 in cross-docking that we identified (Chargui et al., 2018, 2019b). Table 9 shows the resulting search criteria.

This search query resulted in 49 papers, after removing duplicates from Scopus and Web of Science. After an initial screening for which we check whether the papers indeed relate to cross-docking and industry 4.0, we remain with 30 papers. After reading all 30 papers, we find that many papers only consider automation, which we classify as being part of the third industrial revolution, or only used some popular phrases concerning Industry 4.0, but did not discuss the Industry 4.0 contribution in detail nor make a connection with cross-docking. Based on this, we end up with 13 relevant papers on

Industry 4.0 and cross-docking. All papers are published in the period from 2014 up to March 2021.

Table 10 shows the relevant information of the 13 included papers. We show the problem that is considered, the solution approach and the used performance measures, following our initial systematic literature review based on the framework of Ladier and Alpan (2016). Additionally, we show the Industry 4.0 practices that were discussed in the papers.

Most papers discuss the PI, as we already found earlier in the papers by Chargui et al. (2018) and Chargui et al. (2019b). The PI concept relies on several Industry 4.0 aspects: physical objects that are connected in a digital cyber-physical system, machines and sensors that are connected using IoT, M2M communication is necessary and often automated transport and sorting are done with AGVs or other robots. We found an additional source by Chargui, Bekrar, Reghioui, and Trentesaux (2019a) that concerns a similar subject but now applied to a more practical case of a train-to-truck cross-docking terminal. The authors first discuss different types of PI-hubs (road-road, rail-road, water-road) and discuss the use of PI-containers, i.e., smart modular containers that are interconnected with PI-movers (e.g., automatic conveyors, automatic storage and retrieval systems, and AGVs) for automatic transport between PI-nodes (e.g., loading docks and manoeuvring areas). They model a situation where PI-containers are unloaded from a train, sorted and grouped by a PI-sorter and loaded on trucks. Their metaheuristics are used to find optimal solutions for minimizing costs and energy consumption of conveyors. Pawlewski (2015) consider asynchronous multi-modal transport for cross-docking and discuss the potential of the PI. Additionally, they present an MILP for truck-to-door scheduling (Pawlewski, 2015).

In Pach et al. (2014), several future research directions for PI-hubs are listed with a focus on M2M: assignment of PI-containers to PI-hub doors, allocation of PI-containers to transporters and different modalities and the routing of PI-containers in the terminal. As the loading of trucks has proved to be the bottleneck activity in a PI-hub, the authors propose a method using PI-containers that are used to group smaller shipments, to reduce the number of loading movements. They illustrate a grouping approach using the following sequence: (1) the first container arrives at a loading area and sends a grouping proposal to known PI-containers that can be grouped, (2) the containers respond and communicate their arrival time at the loading area, (3) a decision is made on a grouping based on the size of containers, arrival time and grouping policy, and (4) the containers are sent an acceptance or refusal for grouping. The authors test three different grouping policies and compare them with a non-grouping situation. They show that the product throughput time can be reduced by 30% when using a grouping policy (Pach et al., 2014). Similarly, in three papers, Walha, Chaabane, Bekrar, and Loukil (2014), Walha, Bekrar, Chaabane, and Loukil (2016a), and Walha, Bekrar, Chaabane, and Loukil (2016b) discuss PI-hubs and M2M communication. Walha et al. (2016b) study rail-road PI-hubs and the container grouping problem. The authors propose a multi-agent system to generate reactive solutions. Their model consists of three types of agents that communicate with each other and respond to the environment: a supervisor agent, a set of group agents and a set of dock agents. The supervisor agent manages the creation of group agents. Group agents represent a set of containers. The dock agent sends information about dock availability and expected travel distance for containers. Especially with dynamic scenarios with disturbances, their model outperforms static approaches (Walha et al., 2016b). Finally, Sallez, Berger, Bonte, and Trentesaux (2015) propose a hybrid control method for routing inside a PI-hub, i.e., globally optimized routing for a complete PI-hub combined with locally reactive PI-containers that can respond to disturbances. Their model is robust

Table 10. Extended Cross-Docking Literature Review on Industry 4.0.

	Problem	Planning Level	Solution Method	Performance Measures	Industry 4.0 Components
Chargui et al. (2018)	Internal resource operation	Operational – Scheduling/routing	Simulation	Truck processing deviation, makespan, Waiting Time	Cyber-physical systems, IoT, M2M, RFID
Chargui et al. (2019a)	Internal resource operation	Operational – Scheduling/routing	MILP, simulated annealing, tabu search	Truck utilization costs, energy costs	Cyber-physical systems, IoT, M2M
Chargui et al. (2019b)	Internal resource operation, truck-to-door scheduling	Operational – Scheduling/routing	Scheduling heuristic	Truck processing deviation	Cyber-physical systems, IoT, M2M, RFID
Grefen et al. (2019)	Internal resource operation	Operational – Scheduling	-	-	IoT, AGVs
Kusumakar et al. (2018)	Internal resource operation, truck-to-door scheduling	Operational – Allocation/routing	Simulation	Driving precision	IoT, AGV, M2M
Pach et al. (2014)	Truck loading, container grouping	Tactical – Scheduling/ allocation	Heuristics, simulation	Makespan	Cyber-physical systems, IoT, AGV, M2M
Pan et al. (2021)	Truck scheduling, truck-to-door scheduling	Tactical – Scheduling/ allocation	MILP	Makespan	IoT, RFID
Pawlewski (2015)	Truck-to-door scheduling, truck scheduling	Tactical/scheduling	MILP, simulation	Truck driving distance	Cyber-physical systems, IoT, AGV, M2M
Quak, Van Duin, and Hendriks (2020)	Cross-docking interviews	–	–	–	Cyber-physical systems, IoT
Sallez et al. (2015)	Internal resource operations	Operational/routing	Simulation	Makespan, failures	Cyber-physical systems, IoT, AGV, M2M
Walha et al. (2014)	Internal resource operations	Operational/allocation	–	–	Cyber-physical systems, IoT, AGV, M2M
Walha et al. (2016a)	Internal resource operations, grouping containers	Operational/allocation	Heuristics	Number of trucks used, fill rates and travel distance	Cyber-physical systems, IoT, AGV, M2M
Walha et al. (2016b)	Internal resource operations, grouping containers	Operational/allocation	Heuristics, meta-heuristics, simulation	Number of trucks used, fill rates and travel distance	Cyber-physical systems, IoT, AGV, M2M

to unexpected situations, i.e., external disruptions (wrong placement of trucks, lateness of trains) and internal disruptions (conveyor breakdown).

Automated distribution and autonomous systems are other topics present in cross-docking research. Grefen, Brouns, Ludwig, and Serral (2019) discuss a multi-location IoT business process and illustrate this using a case study for the port of Rotterdam. They outline the complete business process of unloading sea containers and transporting them to customs using cranes and AGVs, all interconnected via IoT. The authors illustrate how a sea container can communicate during different moments of the business processes (e.g., request move by crane, open doors for customs). All types of messages described are machine-to-machine communication. They further discuss co-location in general, which is the concept of business processes that need to be executed in physical proximity of each other, e.g., a crane lifts a container at specific GPS coordinates. The paper does not present a mathematical model or quantitative data. In Kusumakar, Buning, Rieck, Schuur, and Tillema (2018), the autonomous manoeuvring of a truck from a parking area to a cross-docking door is discussed. Manoeuvring trucks to doors can be difficult for human drivers; humans might need much time or cause collisions resulting in financial damage. The authors propose a new approach where trucks are autonomously guided to docking doors using unmanned aerial vehicles that are connected to a truck using IoT. Their simulation shows that truck driving precision is high enough for use in practice and is robust for different types of layouts.

Smart sensors and RFID tracking is a topic relevant to automated cross-docking centres and automated sorters. Pan, Zhou, Fan, Li, and Zhang (2021) discuss the use of smart sensors and IoT in perishable goods inventory management and cross-docking. With the use of RFID tags in cross-docking terminals, perishable products can be better tracked and data about shelf-life are more reliable. RFID smart tags can be used to measure light, temperature and humidity near products, which are indicators used for predicting remaining shelf-life (Pan et al., 2021).

Summarizing our extended literature review, we observe that Industry 4.0 practices are being adopted in cross-docking research. Most research deals with PI-hubs and the related Industry 4.0 topics. Some research concerns automated distribution, with a special focus on automated sorting, for which smart sensors/RFID are needed to track physical goods. PI-hub research mainly focusses on the multi-modal transport aspect. Fig. 8 summarizes the frequency of Industry 4.0 practices considered in research, for both our initial search and the extended search.

Gaps and Future Research Directions for Industry 4.0 in Cross-Docking

In the review of Ladier and Alpan (2016), several promising future research directions were identified. These mainly covered gaps in the literature, namely the modelling of mixed service doors for truck loading and unloading, the consideration of uncertainty and deadlines for truck departures, the inclusion of storage capacity in models, the change of performance indicators more related to practice and the inclusion of uncertainty in general. In this section, we evaluate the future research directions mentioned in Industry 4.0 related literature (see Table 11). Since the review of Ladier and Alpan (2016) was oriented on cross-docking in general, there is little overlap in future research directions as identified by Industry 4.0 research. The main future research direction that is recognized by Ladier and Alpan (2016) and by most Industry 4.0 research is the addition of uncertainty, i.e., stochasticity, to the studied cross-docking models.

Fig. 8. Frequency of Industry 4.0 Elements in Research. The number of Related Works is Indicated in Parentheses.

Table 11. Research Directions Identified by Ladier and Alpan and Industry 4.0 Cross-Docking Related Works.

	Future Research Directions
Ladier and Alpan (2016)	Mixed service modes, consider truck departure deadlines and uncertainty, include storage capacity in models, use better performance indicators, include dynamicity and uncertainty in models
Chargui et al. (2018)	Resource allocation for PI-hubs
Chargui et al. (2019a)	Uncertainty (truck delays, order mutation) for PI-hubs
Chargui et al. (2019b)	Internal and external disruptions for PI-hubs
Grefen et al. (2019)	Add additional constraints on co-location, e.g., operating within certain temperature ranges
Kusumakar et al. (2018)	Technical remarks considering enhancing accuracy of the autonomous truck docking
Pach et al. (2014)	Departure time of PI-containers as a performance indicator. Add internal disruptions, consider future states of the system for the routing approach
Pan et al. (2021)	Technical remarks about deterioration rate
Pawlewski (2015)	No concrete future research direction
Quak et al. (2020)	General outlook on cross-docking, no concrete future research directions
Sallez et al. (2015)	Study heterogeneous PI-container sizes, study robustness by allowing backward motions of PI-containers
Walha et al. (2014)	Internal and external disruptions in PI-hubs
Walha et al. (2016a)	Internal and external disruptions in PI-hubs
Walha et al. (2016b)	Internal and external disruptions in PI-hubs, consider the routing problem for PI-containers

The potential of Industry 4.0 for cross-docking in saving costs and running more reliable operations has been shown but requires more research and validation in practice. In Section 'Industry 4.0 Components in Cross-Docking Literature', we discussed the latest literature related to cross-docking and Industry 4.0. We can make general recommendations for future research, based on our findings and the synthesis from the reviewed literature. In this sense, future research can be done in several areas: (1) the development of cyber-physical systems for cross-docking terminals that aid the communication between automated machines and transporters, (2) the further development of automated sorting machines using RFID technology, (3) the search for applications of smart sensors that can aid cross-docking facilities, (4) the internal operations and routing of automated distributed control systems, (5) the assignment of PI containers to PI-hub dock doors, (6) allocation of PI-containers to modalities and transporters, (7) routing of PI-containers inside terminals, using PI-conveyors, AGVs or other PI-nodes and (8) the addition of internal and external disruptions to PI-hubs.

CONCLUSION

In this chapter, we considered cross-docking literature between 2015 and 2020. Based on the literature study by Ladier and Alpan (2016), we did a systematic literature review to investigate to which degree the field of research has changed after their recommendations. We concluded that manual modes of transport remain the most frequently studied approach in cross-docking literature since human workers are perceived as more flexible. However, we showed that developments in technology have huge potential for more automated cross-docking terminals.

Through this review, we showed the use of different modelling constraints and performance indicators. We did not observe large deviations from the observations by Ladier and Alpan (2016). The small deviation compared with Ladier and Alpan (2016) is that more real-world constraints are used, but still, too few studies use mixed door service modes and industry-based performance indicators. Our literature review resulted in only seven papers that considered features of Industry 4.0 in cross-docking. Therefore, we performed an additional review extending the time horizon and removing the focus on practical cases only.

Concerning Industry 4.0, we collected 15 works in our second review. Most deal with PI-hubs, which is a concept for which several components of Industry 4.0 are used: cyber-physical systems, IoT, machine-to-machine communication and AGVs/robotics. Outside the field of the PI, research treated smart sensors for tracking perishable goods, RFID for automated sorters and autonomous distribution for cross-docking facilities. We conclude that Industry 4.0 is gaining attention in cross-docking research but is mainly focussed on PI-hubs. As points of further research, some authors have in common the importance of considering uncertainty and disruptions in PI-hubs, while others point out the incorporation of PI-containers KPI and features.

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