

Cross-docking: state of the art



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 Omega journal homepage: www.elsevier.com/locate/omega Review Cross-docking: State of the art Jan Van Belle n, Paul Valckenaers, Dirk Cattrysse KU Leuven, Department of Mechanical Engineering, Celestijnenlaan 300B, B-3001 Heverlee (Leuven), Belgium a r t i c l e i n f o Article history: Received 23 June 2011 Accepted 17 January 2012 Processed by Pesch Available online 25 January 2012 Keywords: Cross-docking Logistics Classi? cation abstract

Cross-docking is a logistics strategy in which freight is unloaded from inbound vehicles and (almost) directly loaded into outbound vehicles, with little or no storage in between. This paper presents an overview of the cross-docking concept. Guidelines for the successful use and implementation of crossdocking are discussed and several characteristics are described that can be used to distinguish between different cross-dock types. In addition, this paper presents an extensive review of the existing literature about cross-docking. The discussed papers are classi? d based on the problem type that is tackled (ranging from more strategic or tactical to more operational problems). Based on this review, several opportunities to improve and extend the current research are indicated. & 2012 Elsevier Ltd. All rights reserved.

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4. 5. 1. Introduction

Cross-docking is a logistics strategy nowadays used by many companies in different industries (e. g. retail ? rms and less-thantruckload (LTL) logistics providers). The basic idea behind crossdocking is to transfer incoming shipments directly to outgoing Corresponding author. Tel. : ? 32 16322534; fax: ? 32 16322986. E-mail addresses: jan.kuleuven. be (J. Van Belle), paul.kuleuven. be (P. Valckenaers), dirk.kuleuven. be (D. Cattrysse). 0305-0483/\$ - see front matter & 2012 Elsevier Ltd. All rights reserved. doi: 10.1016/j. mega. 2012. 01. 005 n vehicles without storing them in between. This practice can serve differentgoals: the consolidation of shipments, a shorter delivery lead time, the reduction of costs, etc. The role of cross-docking in industry even seems to increase [1-4]. In a traditional distribution center, goods are ? rst received and then stored, for instance in pallet racks. When a customer requests an item, workers pick it from the storage and ship it to the destination. From these four major functions of warehousing (receiving, storage, order picking and shipping), storage and order picking are usually the most costly.

Storage is expensive because of the inventory holding costs, order picking because it is labor intensive. One approach to reduce costs could be to improve one or more of these functions or to improve how they interact. Crossdocking however is an approach that eliminates the two most expensive handling operations: storage and order picking [5–8]. A definition of cross-docking provided by Kinneer [9] is: “receiving product from a supplier or manufacturer for several end destinations and consolidating this product with other suppliers’ product for common final delivery destinations”. In this definition, the focus is on the consolidation of shipments to achieve economies in transportation costs. The Material Handling Industry of America (MHIA) defines cross-docking as “the process of moving merchandise from the receiving dock to shipping [dock] for shipping without placing it first into storage locations” [10]. The focus is now on transshipping, not holding stock. This requires a correct synchronization of incoming (inbound) and outgoing (outbound) vehicles. However, a perfect synchronization is difficult to achieve.

Also, in practice, staging is required because many inbound shipments need to be sorted, consolidated and stored until the outbound shipment is complete. So, this strict constraint is relaxed by most authors. Cross-docking then can be described as the process of consolidating freight with the same destination (but coming from several origins), with minimal handling and with little or no storage between unloading and loading of the goods. If the goods are temporally stored, this should be only for a short period of a time. An exact limit is difficult to define, but many authors talk about 24 h (e. g. [5, 7, 11, 12]). If the goods are placed in a warehouse or on order picking

shelves or if the staging takes several days or even weeks, it is not considered as crossdocking but as (traditional) warehousing. However, even if the products are staged for a longer time, some companies still consider it cross-docking, as long as the goods move from supplier to storage to customer virtually untouched except for truck loading [3, 13]. Many organizations use a mixture of warehousing and cross-docking to combine the benefits of both approaches [1].

A terminal dedicated for cross-docking is called a cross-dock. In practice, most cross-docks are long, narrow rectangles (I-shape), but other shapes are also used (L, T, X, . . .) [5]. A crossdock has multiple loading docks (or dock doors) where trucks can dock to be loaded or unloaded. Incoming trucks are assigned to a 'strip door' where the freight is unloaded. Then the goods are moved to its appropriate 'stack door' and loaded on an outbound truck. Mostly, there is no special infrastructure to stage freight. If goods have to be stored temporarily, they are placed on the floor of the cross-dock (e. . in front of the dock door where the departing truck is or will be docked). However, it is possible that the cross-dock contains for instance a pallet storage, certainly if cross-docking is combined with warehousing. Fig. 1 presents a schematic representation of the material handling operations at an I-shaped cross-dock with 10 dock doors. Incoming trucks are either directly assigned to a strip door or have to wait in a queue until assignment. Once docked, the freight (e. g. pallets, packages or boxes) of the inbound truck is unloaded and the destination is identified (e. g. y scanning the barcodes attached to the goods). Then, the goods are transported to the designated stack door by some material handling device, such as a worker

operating a forklift or a conveyor belt system. There, the goods are loaded onto an outbound truck that serves the dedicated destination. Once an inbound truck is completely unloaded or an outbound truck is completely loaded, the truck is replaced by another truck. Cross-docking corresponds with the goals of lean supply chain management: smaller volumes of more visible inventories that are delivered faster and more frequently [14].

In the literature, several other (possibly intertwined) advantages of cross-docking compared with employing traditional distribution centers and point-to-point deliveries are mentioned (e. g. [2, 3, 6, 15, 16]). Some advantages compared with traditional distribution centers are: cost reduction (warehousing costs, inventory-holding costs, handling costs, labor costs); shorter delivery lead time (from supplier to customer); improved customer service; reduction of storage space; faster inventory turnover; fewer overstocks; reduced risk for loss and damage.

Some advantages of cross-docking compared with point-to-point deliveries are: cost reduction (transportation costs, labor costs); consolidation of shipments; improved resource utilization (e. g. full truckloads); better match between shipment quantities and actual demand. Fig. 1. Material handling at a typical cross-dock. These advantages make cross-docking an interesting logistic strategy that can give companies considerable competitive advantages. Wal Mart is a well-known example [17], but also several other companies have reported the successful implementation of cross-docking (e. . Eastman Kodak Co. [14], Goodyear GB Ltd. [9], Dots, LLC [18] and Toyota [13]). Although cross-docking has already been applied in the 1980s (e. g. by Wal Mart), it has only attracted attention from academia much later and

mostly during the recent years. For instance, more than 85% of the academic papers found by the authors are published from 2004 on. During these years, a considerable number of papers have been published and because of the growing interest from industry [1–4], the authors expect that still more research on this topic will be performed the coming years.

The objective of this paper is to present an overview of the cross-docking concept. First, guidelines for the successful use and implementation of cross-docking will be discussed. Further, several characteristics will be described to distinguish between different types of cross-docks. Next, the paper will provide a review of the existing literature about cross-docking. The discussed papers are classified based on the problem type. These problems range from more strategic or tactical to more operational problems. This review can help (future) cross-docking practitioners to find the correct literature to start or improve their cross-docking operations. Without a proper implementation, it is impossible to benefit from the above-mentioned advantages. Based on the provided review, the authors try to identify gaps of knowledge and interesting areas for future research. The term cross-docking usually refers to the situation in which trucks or trailers¹ are loaded and unloaded at a cross-docking terminal. However, the operations to handle freight at a harbor or airport are sometimes very similar.

At a harbor for instance, containers are unloaded from a ship and temporarily placed onto the quay until they are loaded onto another ship or onto a truck. An airport can also be seen as a kind of cross-dock for transferring passengers and their baggage. In the literature, several papers

can be found that deal with similar problems as encountered in crossdocking, but specific for harbors or airports (e. g. how to determine the layout of an airport terminal [19, 20], how to assign airplanes to gates [21], etc.). These papers are not taken into account for the literature review presented here.

The paper focuses on the typical cross-docking in which goods are transferred between trucks at a cross-dock. The specific application or industry (e. g. less-than-truckload (LTL) or courier, express and parcel (CEP) industry) is not important, as long as the applied material handling can be considered as cross-docking. To the best of our knowledge, only two papers present a review of cross-docking papers. Boysen and Fliedner [2] discuss papers about the truck scheduling problem and provide a classification of the considered problems. The approach taken here is however more general and several problem types related to crossdocking are discussed, including the truck scheduling problem (see Section 4. 6). Agustina et al. [22] provide a general picture of the mathematical models used in cross-docking papers. These models are classified based on their decision level (operational, tactical or strategic) and then subdivided by problem type. However, another classification is presented here as the authors do not completely agree with the proposed classification (the considered problem types and the assignment of papers to problem types).

For instance, Agustina et al. [22] do not consider vehicle routing and temporary storage and the papers about cross-dock networks are discussed in two different sections (transshipment problems and cross-docking network design). Also, some papers about dock door assignment are discussed in the

section about cross-docking layout design. In addition, the review presented here is more extensive; more papers are included and the papers are discussed in more detail. This paper also includes a general overview of cross-docking and describes several cross-dock characteristics. The paper is organized as follows.

The next section discusses in which situations cross-docking is a suitable strategy and deals with the requirements for a successful implementation. In Section 3, the characteristics are discussed that can be used to differentiate between alternative cross-docking systems. The literature review is presented in Section 4. The discussed papers are classified based on the problem type they deal with. The conclusions with opportunities to improve and extend the current research are summarized in Section 5. Fig. 2. Suitability of cross-docking (adapted from Apte and Viswanathan [1]). 2.

When and how to use cross-docking? Although cross-docking is nowadays used by many companies, it is probably not the best strategy in every case and in all circumstances. This section briefly describes the existing literature that gives some guidelines for the successful use and implementation of cross-docking. Apte and Viswanathan [1] discuss some factors that influence the suitability of cross-docking compared with traditional distribution. A first important factor is the product demand rate.

If there is an imbalance between the incoming load and the outgoing load, cross-docking will not work well. Hence, goods that are more suitable for cross-docking are the ones that have demand rates that are more or less stable (e. g. grocery and regularly consumed perishable food items). For these

products, the warehousing and transportation requirements are much more predictable, and consequently the planning and implementation of cross-docking becomes easier. The unit stock-out cost is a second important factor. Because cross-docking minimizes the level of inventory at the warehouse, the probability of stock-out situations is higher.

However, if the unit stock-out cost is low, the benefits of cross-docking can outweigh the increased stock-out cost, and so cross-docking can still be the preferred strategy. As shown in Fig. 2, cross-docking is therefore preferred for products with a stable demand rate and low unit stock-out cost. The traditional warehousing is still preferable for the opposite situation with an unstable demand and high unit stock-out costs. For the two other cases, cross-docking can still be used when proper systems and planning tools are in place to keep the number of stock-outs to a reasonable level. Some other factors that can influence the suitability of crossdocking are the distance to suppliers and customers (higher distances increase the benefits of consolidation), the product value and life cycle (a larger reduction in inventory costs for products with a higher value and shorter life cycle), the demand quantity (a larger reduction in inventory space and costs for products with a higher demand), the timeliness of supplier shipments (to ensure a correct synchronization of inbound and outbound trucks), etc. [1, 23, 24]. Some authors use a more quantitative approach to study the suitability of cross-docking. For instance, Galbreth et al. [6] compare the transportation and handling costs between a situation in which a supplier has to ship goods to several customers with only direct shipments and a situation in which also indirect shipments via a cross-dock are possible. For the second

situation, a mixed integer programming (MIP) model is proposed to determine which goods should go directly from supplier to customer and which goods should be shipped via a cross-dock to meet the (known) demands. The transportation costs are modeled in a realistic way: fixed for truckload shipping, while the less-than-truckload shipping costs are modeled using a modified all-unit discount (MAUD) cost function. The holding costs at the customers are proportional to the quantity and the holding time between arrival time and due date. The costs for the two situations are compared under varying operating conditions. The authors conclude that cross-docking is more valuable when demands are less variable and when unit holding costs at customer locations are higher.

On the other hand, it is less valuable when the average demands are close to truck load capacity. Other quantitative approaches make a comparison between a situation with a cross-dock and a situation with a traditional distribution center. For instance, Kreng and Chen [25] compare the operational costs. Besides the transportation and holding costs, the production costs (more specifically the setup costs) of the goods at the supplier are taken into account. When a cross-dock is used, more frequent deliveries to the cross-dock are required and the batch size needs to be smaller, which causes higher setup costs.

Waller et al. [26] look to both situations from an inventory reduction perspective. Schaffer [8] discusses the successful implementation of crossdocking. When a company wants to introduce cross-docking, the

introduction should be prepared very well. If the necessary equipment is already available and because cross-docking seems simple, one easily assumes that cross-docking can be implemented without much effort. However, cross-docking itself is quite complex and requires a high degree of coordination between the supply chain members (e. g. the timing of arrival and departure).

So, the requirements for successful cross-docking should be understood thoroughly and the implementation should be planned carefully. In [8], Schaffer elaborates on six categories of requirements for a successful implementation. According to Witt [13] and to Yu and Egbelu [27], software to plan and control the cross-docking operations (e. g. a warehouse management system or WMS) plays an important role in the successful implementation of cross-docking. The required (automated) hardware for a cross-docking system (material handling devices, sorting systems, etc.) might come off the shelf and is easily available today.

But the software needs to be tailored to the specific requirements and is in general relatively less developed, although it is as important as hardware to cross-docking success. This is also confirmed by a survey among professionals who are involved in cross-docking and who denote IT system support as a key barrier to effective cross-docking [3, 4]. Hence, the system requirements need to be carefully defined and studied in order to prevent installing the physical system to discover afterwards there is no information and communications system in place for successful operation.

This software system can only work correctly if it is fed with accurate and timely information. Compared with regular distribution, the information flow

to support cross-docking is significantly more important [24]. For instance, to coordinate the inbound and outbound trucks to the appropriate docks, the arriving time and the destination of the freight need to be known before the physical arrival of the goods (e. g. via advance shipping notice (ASN)). Several information technology tools are available to realize this information flow, e. g. electronic data interchange (EDI), shipping container marking (SCM), bar-coding and scanning of products using universal product code (UPC) [1]. Regardless of which technology is chosen, the supply chain partners must be able and willing to deliver the required information via this technology. A good cooperation across the supply chain can make or break the cross-docking implementation [8, 13, 24]. In a two-touch or single-stage cross-dock, products are received and staged on the dock until they are loaded for outbound transportation. Usually, the goods are put into zones corresponding to their strip or stack door (see Fig. 3).

In the case of a multiple-touch or two-stage cross-dock, products are received and staged on the dock, then they are reconfigured for shipment and are loaded in outbound trucks. In a typical configuration, the incoming freight is first put in zones corresponding to the strip doors. The goods are then sorted to the zones corresponding to the stack doors (see Fig. 4). Another distinction can be made according to when the customer is assigned to the individual products [30]. In predistribution cross-docking, the customer is assigned before the shipment leaves the supplier who takes care of preparation (e. g. labeling and pricing) and sorting.

This allows faster handling at the cross-dock. On the other hand, in post-distribution crossdocking, the allocation of goods to customers is done at the

cross-dock. Still some other distinctions are possible. The German supermarket retailer Metro-AG for instance distinguishes source-oriented and target-oriented cross-docking based on the location Fig. 3. A single-stage cross-dock in which the products are staged in zones corresponding to the stack doors (adapted from Gue and Kang [28]).

3. Cross-dock characteristics

Several characteristics can be considered to distinguish between various types of cross-docks (and cross-docking).

A common distinction made in the literature is based on the number of touches [3] or stages [28]. In one-touch cross-docking, products are touched only once, as they are received and loaded directly in an outbound truck. This is also called pure cross- Fig. 4. A two-stage cross-dock in which the products are staged in zones corresponding to the strip and stack doors and are sorted in between (adapted from Gue and Kang [28]).

J. Van Belle et al. / Omega 40 (2012) 827–846 831 of the cross-docking terminals relative to suppliers and customers [31].

Napolitano [32] distinguishes several types of cross-docking based on the intended use and in [29], eight different crossdocking techniques are listed. In this section, several characteristics are described that can be used to distinguish between different cross-dock types. 3 Note that real world characteristics of the cross-dock are considered, and not the properties from a speci? c decision problem related to cross-docking. For the papers included in the literature review (Section 4), the characteristics of the considered cross-docks will be listed in tables according to the characteristics described here. However, the structure of Section 4 is not based on these characteristics, but on the considered problem type. The characteristics can

be divided into three groups: physical characteristics, operational characteristics and characteristics about the flow of goods. In the next sections, these groups will be described in more detail.

1. Physical characteristics

The physical characteristics are characteristics of the crossdock that are supposed to be fixed (for a rather long time). The following physical characteristics are considered. Shape: Cross-docks can have a large variety of shapes.

The shape can be described by the letter corresponding to the shape: I, L, U, T, H, E, . . .

Number of dock doors: A cross-dock is also characterized by the number of dock doors it has. In practice, cross-docks range in size from 6 to 8 doors to more than 200 doors, and even a cross-dock with more than 500 doors exists [33]. In the literature, sometimes the number of dock doors is limited to only 1 or 2. In these cases, the idea is not to model a realistic cross-dock, but to gain some insight by studying a simplified model.

Internal transportation: The transportation inside the crossdock can be executed manually (e.g. by workers using forklifts) or there can be an automated system in place (e.g. a network of conveyor belts). The available infrastructure will of course be dependent on the type of freight that is handled in the cross-dock. For instance, LTL carriers handle mostly palletized freight and so make use of forklifts. Conveyor systems on the other hand are among others used by parcel carriers, as they deal with many (small) packages. A combination of both transportation modes is also possible.- 2. Operational characteristics

Some operational decisions can influence the functioning of the cross-dock.

These operational constraints lead to the following characteristics. Service mode: According to Boysen and Fliedner [2], the service mode of a cross-dock determines the degrees of freedom in assigning inbound and outbound trucks to dock doors. In an exclusive mode of service, each dock door is either exclusively 3 Some of the characteristics described here are similar to the characteristics used by Boysen and Fliedner [2] to make a classification of truck scheduling problems. However, they [2] consider not only real world characteristics, but also characteristics of the (mathematical) models. At least for the papers in which these characteristics are described, i. e. , in which real world details of the cross-dock are considered (Sections 4. 5–4. 8). 5 This classification is rather vague. For some characteristics, it is not clear in which group they fit best or they can be assigned to multiple groups. For instance, temporary storage is considered as a low characteristic. However, temporary storage can also be seen as a physical characteristic (storage is not possible because of space constraints) or operational characteristic (it can be an operational decision that storage is not allowed, e. . to avoid congestion inside the cross-dock). dedicated to inbound or outbound trucks. If this service mode is used, mostly one side of the cross-docking terminal is assigned to inbound trucks and the other side to outbound trucks. A second mode is mixed mode. In this mode, inbound and outbound trucks can be processed at all doors. These two modes can also be combined. In this combination mode, a subset of doors is operated in exclusive mode while the rest of the doors is operated in mixed mode. Pre-emption: If pre-emption is allowed, the loading or unloading of a truck can be interrupted.

This truck is then removed from the dock and another truck takes its place. The unloaded truck has to be docked later on to finish the loading or unloading.

3.3. Flow characteristics

The characteristics of the flow of goods that have to be processed by a cross-dock can be very different. The following characteristics are distinguished.

Arrival pattern: The arrival times of the goods are determined by the arrival times of the inbound trucks. The arrival pattern can be concentrated at one or more periods if the inbound trucks arrive together at (more or less) the same times.

For instance, a cross-dock in the LTL industry serving a certain geographical area usually receives freight at two periods. Goods that have to be transported from inside that area to another area are picked up during the day and all pickup trucks arrive in the evening at the cross-dock. The goods are then sorted during the night and the outbound trucks leave in the morning. To simplify the problem, several papers assume that the inbound trucks arrive together (at the beginning of the time horizon). On the other hand, freight from outside the region but destined for that area arrives in the early morning and is then distributed during the day. Another possibility is that the arrival pattern is scattered and the inbound trucks arrive at different times during the day. The arrival pattern has an influence on the congestion of the cross-dock and on the scheduling of workers and resources.

Departure time: The departure times of the trucks can be restricted or not. In many cases there are no restrictions and the trucks leave the cross-dock after all freight is loaded or unloaded. However, it is also possible that the trucks have to depart before a certain point in time, for instance in order to be on time for a next transportation task.

In this case, there can be restrictions imposed on the departure times of the inbound trucks only, so that these trucks have to be unloaded on time. In a similar way, it is possible that only the outbound trucks have to leave the cross-dock before a certain moment. ⁶ For instance, in the parcel delivery sector, the outbound trucks usually leave at a fixed point in time. Parcels arriving late have to wait until another truck departs for the same destination. It is also possible that both inbound and outbound trucks have restricted departure times.

Product interchangeability: The freight handled at a cross-dock is in general not interchangeable. In this case, all products are dedicated to a specific destination⁷ or a specific outbound truck (pre-distribution). Information about the destination or the dedicated truck is normally known before the products arrive at the cross-dock. It is however also possible that interchangeability of products is allowed (post-distribution). In this situation, only the type of products to be loaded on the outbound trucks and the corresponding quantity is known (see footnote 7).

When the products are interchangeable, usually some value-added activities (e. g. labeling) need to be performed. ⁶ This point in time can be dependent on the (due dates of the) actual load of the truck. ⁷ The assignment of the products to a specific outbound truck is then an operational decision. ⁸³² J. Van Belle et al. / Omega 40 (2012) 827–846 Temporary storage: In pure cross-docking, the arriving freight is directly transported to outbound trucks, so no storage is needed. In practice however, this is rarely the case. In general, the goods are temporarily stored on the floor of the cross-docking terminal (e. . in front of the stack doors) or even in a (small) warehouse.

However, it is possible that goods are not allowed to be stored. For instance, if refrigerated products have to be cross-docked in a non-cooled terminal, these products have to be directly moved from a cooled inbound to a cooled outbound truck. 4. Literature review Cross-docking practitioners have to deal with many decisions during the design and operational phase of cross-docks. These decisions can have a serious impact on the efficiency, so they have to be carefully taken. In the literature, several decision problems are studied.

Some of these problems are more concerned about decisions with effects on a longer term (strategic or tactical), while others deal with short-term decisions (operational). This section gives a review of the existing literature about crossdocking problems. The literature review is structured according to the basic planning process a manager, wanting to start with cross-docking, is confronted with. The first decisions that have to be taken during the planning process are strategic decisions: where will a cross-dock (or crossdocks) be located and what is the best layout of a cross-dock.

Once the cross-dock is available, it will be part of a supply network (with one or more cross-docks). A tactical decision that has to be made then is how the goods will flow through the network to minimize the costs, while making supply meet demand. Next, the manager is faced with the operational decision (although it has also tactical aspects) of vehicle routing: before arriving at the cross-dock, freight has to be picked up at various locations, and the goods have to be delivered to multiple locations after consolidation at the cross-docking terminal.

Other operational decisions deal with the assignment of trucks to dock doors or the scheduling of the trucks, and with the location where goods will be

temporarily stored. Of course, the manager will also be confronted with problems that are not specific for cross-docking: the scheduling of the internal resources for the loading and unloading of the freight (e. g. the workforce), choosing the best staging strategy and determining an optimal truck packaging sequence. The next sections describe the cross-docking problems dealt with in the literature.

Only the problems that are specific for cross-docking are considered. First, the strategic decisions are discussed: the location of cross-docks and layout design. The tactical problem of cross-docking networks is described next. Further, the operational decisions are handled: vehicle routing, dock door assignment, truck scheduling and temporary storage. Finally, some papers that study other issues related to crossdocking are discussed.

4. 1. Location of cross-docks

The location of one or more cross-docks is part of the design of a distribution network or supply chain.

An important strategic decision that has to be made concerns the position of these crossdocks. This problem cannot be handled isolated from the decisions that determine how the goods flow through this network. The determination of the flow of goods is discussed in Section 4. 3, but problems that also involve a decision about the location are considered here. The problem where to locate facilities (e. g. distribution centers or plants) has attracted a considerable amount of attention. 8 The papers discussed in this section determine additionally the optimal flow of goods through the network.

Moreover, they regard the facilities to be cross-docks because they explicitly take individual vehicles into account or because temporary storage is not

allowed. A first study about the location of cross-docks is performed by Sung and Song [34]. In the considered problem, goods have to be transported from supply to demand nodes via a cross-dock (direct shipments are not allowed). The cross-dock can be chosen from a set of possible cross-dock locations, each with an associated fixed cost. The demands are assumed to be known and there are two types of vehicles with a different capacity and cost. The aim is to find which cross-docks should be used and how many vehicles are needed on each link in order to minimize the total cost. This total cost consists of the fixed costs of the used cross-docks and the transportation costs. The authors present an integer programming model of the problem. This model is very similar to the model presented by Donaldson et al. [35] and Musa et al. [36] (discussed in Section 4.3) and similar simplifying assumptions are applied. Compared with these two papers however, the approach of Sung and Song [34] does not consider direct shipments but does include the location decision.

Because the problem is NP-hard, a tabu search-based algorithm is proposed to solve the problem. The solutions determine how the goods flow through the network. Based on this flow, the number of vehicles can be derived by solving a subproblem. Some computational experiments are performed on generated test instances and indicate that the proposed algorithm finds good feasible solutions within a reasonable time. Sung and Yang [37] extend this work and propose a small improvement to the tabu search algorithm.

The authors also present a set-partitioning-based formulation of the problem and propose a branch-and-price algorithm based on this formulation to obtain exact solutions. The computational results show that this algorithm

gives better results in terms of the number of (smallscale) problem instances solved and the required computation time compared with the results obtained by solving the integer programming model with the optimization software package CPLEX. ?? Gumus and Bookbinder [38] study a similar problem, but now direct shipments are allowed and multiple product types are considered (multicommodity).

The facility cost for each crossdock consists of a fixed cost and a throughput cost charged per unit load. The transportation cost also has two components: a fixed cost for each truck and a variable cost per unit load per unit distance. A last cost that is taken into account is the cost for intransit inventory. In this approach, the synchronization of inbound and outbound trucks is not taken into account. The authors provide a mixed integer programming model of the problem. By solving several smaller problem instances optimally (with the optimization software packages LINGO and CPLEX), the influence of several cost parameters is studied. The authors conclude that the optimal number of cross-docks is an increasing function of the ratio between the (fixed) truck cost and the (fixed) facility cost. A different approach is taken by Jayaraman and Ross [39]. They study a multi-echelon problem in which goods (from multiple product families) have to be transported from a central manufacturing plant to one or more distribution centers. From there, the goods are moved via cross-docks to the customers. The problem is tackled in two stages. In the first stage, a strategic model is used to select the best set of locations for the distribution centers and cross-docks. The authors provide an integer programming formulation that aims to minimize the fixed costs associated with operating open distribution centers

and cross-docks and the 8 Several references can be found in the papers discussed in this section. J. Van Belle et al. / Omega 40 (2012) 827–846 833 various transportation costs. Demand splitting is not allowed: customers have to be assigned to single cross-docks while crossdocks have to be assigned to single distribution centers only.

In the second stage, an operational model decides upon the quantities of each product type that need to be transported via distribution centers and cross-docks. The model tries to minimize the transportation costs while satisfying customer demand. This model is less restrictive than the 1st model (it relaxes for instance the demand splitting assumption) and can be executed once the open distribution centers and cross-docks are determined with the help of the 1st model. Both models are more simplified compared with the previous approaches.

For instance, individual vehicles are not considered and the transportation cost is proportional to the quantity to ship. The authors propose a simulated annealing approach to solve larger problem instances. The computational experiments on generated problem instances indicate that the heuristic gives results with a deviation of about 4% of the optimal solution (obtained with LINGO), but 300–400 times faster. In [40], the same authors present two other heuristics to tackle the problem. Both heuristics are based on simulated annealing but use an extra mechanism to avoid locally optimal solutions.

The 1st heuristic makes use of a tabu list, the second heuristic allows a sudden re-scaling of the ‘system temperature’. For both heuristics, the solution quality and computational performance are tested for different ‘

cooling schemes'. The experimental results indicate that the simulated annealing heuristic combined with tabu search gives better solutions in slightly more time. Bachlaus et al. [41] also consider a multi-echelon supply chain network, including suppliers, plants, distribution centers, crossdocks and customers. The goal is to optimize the material flow throughout the supply chain and to identify the optimal number and location of suppliers, plants, distribution centers and crossdocks. The problem is formulated as a multi-objective optimization model that tries to minimize the total cost and to maximize the plant and volume flexibility. Because of the computational complexity of the problem, the authors propose a variant of particle swarm optimization (PSO) to design the supply chain. Some computational experiments are conducted and the results show that the proposed solution approach gives better results than a genetic algorithm and two other PSO variants. This is at the cost of additional corners which reduce the labor efficiency (two inside and two outside corners for T, four inside and four outside corners for X). An inside corner renders some doors unusable, while doors around an outside corner have less floor space available to stage freight. So, these additional corners are an added cost, which begins to pay off for larger docks. It is however not always easy to predict which shape is better, because this also depends on e. g. the freight flow pattern. Other papers deal with the design of the storage area where the freight can be temporarily staged (on the floor or in racks). In many cases, the freight is placed in several parallel rows and the workers can move between these rows. Vis and Roodbergen [16] deal with the operational decision where to temporarily store incoming freight (see Section 4.7). The proposed algorithm can also be used during the design phase to determine the optimal number of parallel

storage rows and their lengths. The (single-stage or two-stage) storage area can also be organized in parallel lanes directly next to each other which can only be accessed at both ends.

Gue and Kang [28] make use of simulation to study the behavior of these so-called staging queues. The results suggest that, for a single-stage storage area, it is better to have more short lanes than fewer long ones, at least when the workers follow a rational approach. The results also indicate that two-stage cross-docking has a significantly lower throughput than single-stage cross-docking.

4. 3. Cross-docking networks

Some authors do not study problems concerning a single cross-dock, but consider a network that contains one or more cross-docks.

The aim is to determine the flow of goods through such a network in order to reduce costs, while making supply meet demand. The research of Lim et al. [42] extends the traditional transshipment problem. The transshipment problem consists of a number of supply, transshipment and demand nodes. The arcs between these nodes have different capacity limits and costs. The objective is to find a minimum cost flow that meets all demands and the capacity constraints. In the extended transshipment problem, storage is allowed at the transshipment centers.

These centers can be considered as cross-docks because the aim of the model is to minimize or eliminate holdover inventory. Moreover, this problem takes supplier and customer time windows into account and considers the capacity and holding costs of the crossdocks. All shipments have to pass via a cross-dock, so no direct shipments are considered. Similar to the original problem, the objective is to minimize the total cost (transportation costs and

holding costs) while meeting demand and respecting the time windows and capacity constraints.

If multiple departures and deliveries within a time window are allowed (multiple shipping– multiple delivery), the authors show that a time-expanded network can be used to formulate the problem as a minimum cost flow problem (MCFP) which can be solved in polynomial time. For other cases, the authors prove that the problem is NP-hard. For the special case when only one delivery or departure is allowed within a time window and the departure and arrival times are fixed (single shipping–single delivery with fixed schedules), a genetic algorithm is developed by Miao et al. [43].

This heuristic gives better results (in terms of solution quality and computation time) than solving the integer programming formulation of the problem with CPLEX (with a time limit). Chen et al. [44] study a similar problem which they call the multiple cross-dock problem. The major differences are that supplies and demands are not-splittable and that different products can be considered (multicommodity flow problem). Also, transportation time is in this approach not taken into account.

4. 2. Layout design

Once the location of a cross-dock is determined, another strategic decision that has to be made is to choose the layout of the cross-dock.

The layout is interpreted as the dimension and shape of the cross-dock, as well as the dimension and shape of the internal cross-dock areas and their arrangement. Bartholdi and Gue [5] focus on the shape of a cross-dock. Most existing cross-docks are long, narrow rectangles (I-shape), but there are also cross-docks shaped like an L, U, T, H or E. The crossdock shape is sometimes determined by simple constraints (e. g. size and shape of the lot on which it

will stand), but in this paper the focus is on how the shape affects cross-dock performance.

Several experiments are performed in which the labor costs (estimated by the total travel distance)⁹ are measured for different shapes. The experiments suggest that an I-shape is the most efficient for smaller cross-docks (fewer than about 150 doors). For docks of intermediate size, a T-shape is best and for more than 200 doors (approximately) an X-shape is best. Cross-docks with a T or X-shape have a greater ‘centrality’. However, they achieve ⁹ Here and in the following pages, the travel distance is the distance traveled (by workers, forklifts, . . .) in order to transfer the goods internally from the inbound to the outbound truck. 834 J. Van Belle et al. / Omega 40 (2012) 827–846 An integer programming formulation of the problem is provided, together with a proof of its NP-completeness. The authors propose three heuristics (simulated annealing, tabu search and a combination of both) to solve the problem. These heuristics provide better solutions than those obtained by solving the integer programming formulation with CPLEX, within only less than 10% the time used by CPLEX.

Among the three heuristics, tabu search seems to give the best results. The previous studies represent the shipment of goods as flows. Individual transportation units are not considered and the transportation cost is proportional to the quantity to ship. However, to take advantage of consolidation, the vehicle transportation cost should be taken into account. A first approach that does consider the transportation vehicles explicitly (and this is why the authors regard it as cross-docking) is taken by Donaldson et al. [35].

In the considered problem, the goal is to determine whether to route freight directly from suppliers to customers or via a cross-dock and how many vehicles should be scheduled on each transportation link in order to minimize the transportation costs. Compared with the previous approaches however, this problem is more simplified, e. g. storage at the cross-docks is not considered and the synchronization of inbound and outbound trucks is left out of the problem. The authors eliminate links with a large transportation time in an attempt to consider time windows.

However, when the due dates at the destination nodes can vary for the different goods, it is possible that the vehicle allocation of an obtained solution violates the due dates in practice. The authors present an integer programming model of the problem. Because the problem is difficult to solve with branch-and-bound algorithms, an alternative approach is proposed. In this approach, an iterative procedure is used in which either the integrality restrictions on the links from origin nodes to the cross-docks or on the links from the cross-docks to the destination nodes are relaxed.

This relaxation heuristic provides near optimal solutions in an acceptable time. The authors used this approach to compare several scenarios (with a different number of cross-docks at different places) for the network design of a postal service company. The same problem is also studied by Musa et al. [36]. They propose an ant colony optimization (ACO) heuristic to solve the problem and show that this heuristic gives in a short time slightly better results than a branch-and-bound approach (with the optimization software package LINDO) that requires a much longer time.

The approach of Ma et al. [45] takes most of the above-mentioned concerns into account. The so-called shipment consolidation problem (SCP) considers supplier and customer time windows and also the transportation times between the network nodes. Moreover, storage at the transshipment centers (cross-docks) is taken into account, shipments can be transported directly to their destination or via a cross-dock and the transportation cost accounts for the number of trucks. However, only one type of products is considered (single commodity).

Again, the objective is to minimize the total cost (transportation and inventory cost) while satisfying the constraints imposed by the time windows. The authors present an integer programming model of the problem and show that it is NP-complete in the strong sense. Therefore, the authors propose a (two-stage) heuristic algorithm to solve the problem. The basic idea of the algorithm is to consider n trucks that can be fully loaded and then to find solutions that combine several smaller loads that are not considered yet. In the first stage, a full truckload plan (TL plan) and an initial less-than-truckload plan (LTL plan) are constructed. In the second stage, this initial LTL plan is improved iteratively by using a metaheuristic (squeaky wheel optimization or genetic algorithm). The computational experiments indicate that the proposed heuristic gives competitive results compared to CPLEX (with a time limit) within a much shorter time.

4. 4. Vehicle routing

Freight destined for a cross-dock needs in many cases to be picked up at various locations, and has to be delivered to multiple locations after consolidation at the cross-dock.

Both the pickup and the delivery process can be seen as a vehicle routing problem and some studies consider cross-docking and vehicle routing simultaneously. A first approach is taken by Lee et al. [46]. The aim is to find an optimal routing schedule for pickup and delivery (within the planning horizon) that minimizes the sum of transportation cost and fixed costs of the vehicles. It is assumed that split deliveries are not allowed and all pickup vehicles should arrive at the crossdock simultaneously to prevent waiting times for the outbound trucks. While this can be a valid constraint for some cases (see Section 3.), this is not generally true. The authors present an integer programming model of the problem, which however seems unsatisfactory to solve the described problem. A tabu search algorithm is proposed to find solutions. This approach corresponds to the solving of two vehicle routing problems (one for pickup and one for delivery). The second routing problem can only start when the first one is finished and the complete process has to be finished within a certain planning horizon. Liao et al. [47] propose another tabu search algorithm to solve the same problem. Wen et al. [12] study the so-called vehicle routing problem with cross-docking (VRPCD). In this problem, orders from suppliers have to be picked up by a homogeneous fleet of vehicles. These orders are then consolidated at a cross-dock and immediately delivered to customers by the same set of vehicles, without intermediate storage at the cross-dock. During the consolidation, goods are unloaded from the inbound vehicles and reloaded on outbound vehicles. The unloading must be completed before reloading starts. The authors assume that the duration of the unloading consists of a fixed time for preparation and a duration proportional to the load size. It is also assumed that if the delivery will be executed by the same vehicle as used for

pickup, the unloading is not necessary (independent of the sequence in which the vehicle is loaded during the pickup tour). A time window is defined for all suppliers and customers and orders are not splittable. In the case without consolidation, the solution of this problem can be found by solving two vehicle routing problems (one for pickup and one for delivery). Because of the consolidation however, the pickup and delivery routes are not independent.

Only trying to minimize the distance of the pickup and delivery routes is not sufficient, the exchanges of orders at the cross-dock also have to be taken into account. These two aspects usually conflict with each other. The authors present a mixed integer programming formulation of the problem in which the objective is to minimize the total travel time of all vehicles. This formulation contains many variables and constraints, so the authors propose to use tabu search embedded within an adaptive memory procedure. This method is tested on realistic data involving up to 200 supplier-customer pairs.

Experimental results show that the algorithm can produce solutions less than 1% away from the optimum within short computing times (less than 5 s) for small problem instances. For larger instances, the gap with a lower bound is less than 5% while the computation time stays below 5 min.

4. 5. Dock door assignment

When an inbound or outbound truck arrives at the cross-dock, it has to be decided to which dock door the truck should be assigned. A good assignment can increase the productivity of the cross-dock and can decrease the (handling) costs. So, the dock door assignment problem tries to find the 'optimal' assignment of inbound and outbound trucks to dock doors. It is

assumed that there are at least as much dock doors as trucks, so each truck will J. Van Belle et al. / Omega 40 (2012) 827–846 835 Table 1 Characteristics of the papers discussed in Section 4. 5. An ‘ n’ indicates that not a single value of the characteristic is valid, but that all values can be used, ‘ ns’ indicates that a characteristic is not speci? ed. Paper(s) Shape No. of doors n n n n n n n n n n n n n Internal transport Manually Manually Manually Manually Manually n Service mode Exclusive Exclusive Exclusive Exclusive Exclusive Exclusive

Exclusive Exclusive Mixed Exclusive Mixed Exclusive Interchangeability Temporary storage Yes No ns ns ns Yes ns Yes Yes ns ns ns Peck [48] Tsui and Chang [49, 50] ? Bermudez and Cole [51] Cohen and Keren [52] Oh et al. [53] Bartholdi and Gue [54] Gue [33] Brown [55] (semi-permanent) Brown [55] (dynamic) Bozer and Carlo [56] (semi-permanent) Bozer and Carlo [56] (dynamic) Yu et al. [57] | | n | | | | n n n n n Manually Manually Manually Manually Manually Manually Manually Truck Destination Destination Destination Destination Truck Destination Truck Destination e assigned to a different door and time aspects are not taken into account. If this condition is not ful? lled, the dock doors can be seen as (scarce) resources that have to be scheduled over time. This is the so-called truck scheduling problem. Both problems can be quite complex due to the number of doors and the dynamic nature of the problem. This section deals with the dock door assignment problem, while truck scheduling problems are discussed in Section 4. 6. The assignment of dock doors can be executed on a mid-term or short-term horizon [2].

Several papers solve the assignment problem on a mid-term horizon. Then, each dock door serves a specific inbound or outbound destination for a longer period of time (e. g. 6 months).¹⁰ All trucks coming from the same origin or having the same destination are assigned to the same dock. Such a fixed assignment is easier for workers because they know exactly to which dock door they need to ship each load, but it comes at the expense of a reduced flexibility. Even if a fixed assignment is used, it is important that the dock doors are reassigned when there is a significant change in the shipping pattern.

When data about the inbound trucks are known far enough in advance, the assignment of the trucks can be solved on a short-term horizon. The trucks themselves are assigned to the dock doors based on the actual freight flow. This ‘floating dock’ concept is put forward by Peck [48] who studied the material handling operations in an LTL terminal. Such an assignment implies that the workers are every day confronted with a different door for the same destination and have to take care that the freight is loaded into the correct truck. The use of modern information technology (e. g. bar code or RFID scanning together with a WMS) can be useful for this end. A combination of both is also possible. Several papers consider a cross-dock in which destinations are assigned to stack doors (so the outbound trucks are assigned on a mid-term horizon), while the assignment of the inbound trucks is done on a short-term horizon. The characteristics of the cross-docks considered in the following papers are summarized in Table 1. As time aspects are neglected and there are enough available dock doors, the

preemption, arrival pattern and departure time characteristic are not relevant here and are not shown.

In his dissertation, Peck [48] develops a detailed simulation model of an LTL terminal and tries to assign the trucks to dock doors in order to minimize the travel time¹¹ of the shipments. It is assumed that the travel time to transport the products between This includes that the cross-dock operates in exclusive service mode. Here and in the following pages, the travel time is the time required to transfer the goods internally from the inbound to the outbound truck. ¹¹ 10 two trucks can be expressed as a function of the distance, based on the actual contents of the trucks and the required means of transport (2-wheeler, 4-wheeler or forklift).

The designation of doors as either strip or stack doors is ? xed beforehand. The problem is formulated as an integer programming model and because of the computational complexity, a heuristic (greedy balance algorithm) is provided to solve it. Simulation shows that his heuristic improves an assignment based on experience and intuition. Another early study about the assignment of trucks to dock doors is performed by Tsui and Chang [49]. In this paper, a crossdock is considered in which no storage is provided; all shipments go directly from inbound to outbound trucks.

The problem is solved on a mid-term horizon, so the origins and destinations have to be assigned to dock doors, not the trucks itself. The designation of doors as strip or stack doors is ? xed. The assignment problem is formulated as a bilinear programming problem that tries to minimize the travel distance of the forklifts (the number of forklift trips required to carry a certain load is

assumed to be known). To solve it, the authors propose a simple heuristic method to find a local optimum.

The authors do not provide test results, but conclude that the found solution can serve as a good starting point for the cross-dock manager. There exist exact algorithms to solve bilinear optimization problems, but these are not very suited for this problem as the same authors mention in Tsui and Chang [50]. In this paper, a branch-and-bound algorithm is proposed to solve the dock door assignment problem exactly. The numerical tests show that this algorithm is however computational expensive. Bermudez and Cole [51] deal with a very similar problem, but now there is no fixed designation for the doors. All doors can have assigned either an origin or a destination. The mathematical model of Tsui and Chang [49] is adapted to take this into account. The objective function minimizes the total weighted travel distance instead of the real travel distance. A genetic algorithm (GA) is propose