Assemble-to-order systems: a review

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Assemble-to-order systems: A review

Zümbül Atan^{a,*}, Taher Ahmadi^a, Clara Stegheuis^b, Ton de Kok^a, Ivo Adan^a^a Department of Industrial Engineering and Innovation Sciences, Postbus 513, 5600 MB, Eindhoven, The Netherlands^b Department of Mathematics and Computer Science, Postbus 513, 5600 MB, Eindhoven, The Netherlands

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ABSTRACT

In this paper, we review the recent literature on assemble-to-order systems. Each assemble-to-order system consists of multiple components and end-products. The components are assembled into the end-products after information on customer demand is received but the decision on what components to procure or produce must be made well before demand materializes. Most of the research in this area aims to find good operating policies to minimize system-wide cost subject to a customer service level. An operating policy of an assemble-to-order system is a combination of a component replenishment/production policy and an inventory allocation policy of these components. The last review on assemble-to-order systems dates back to Song and Zipkin (2003). The literature has been growing quickly in the past few years. Since 2003 more than 100 papers have been published in major operations research and management science journals. We review these papers to serve as a reference for researchers working in the field and as a starting point for those who wish to begin to explore it.

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1. Introduction

Strategic advantages of mass customization and delayed differentiation are undeniable. Manufacturing companies that benefit from these advantages manage to deal with the challenge of balancing their demand and supply. These companies rely on multiple operational strategies to achieve this balance. For selection of the best strategy it is important to find out how deeply the customer order penetrates into a company's supply chain. Customer order decoupling point refers to the point in the supply chain at which a customer triggers the production activities (de Kok & Fransoo, 2003). Based on the concept of the customer order decoupling point, Ari Samadhi and Hoang (1995) categorize production environments in four categories; make-to-stock (MTS), assemble-to-order (ATO), make-to-order (MTO), and engineer-to-order (ETO). Fig. 1 depicts the customer order decoupling points for each of these production environments.

In make-to-stock production environment, the final products are produced and kept in inventory ahead of customers demand. The inventory may not fully conform to future customer demand and may result in a demand-supply mismatch in the form of left-over of inventory or shortage of inventory. Therefore, in make-to-stock manufacturing systems, inventory planning, lot size determination and demand forecasting are crucial operational issues. By

adapting one of the other three strategies, manufacturers attempt to delay the production of the final products until they obtain better or complete demand information. One of the most popular strategies is the assemble-to-order strategy. In this study, we restrict our attention to this strategy and refer to the manufacturing systems which operate using it as “assemble-to-order systems”.

In general, assemble-to-order systems consist of multiple components, which often are complex subassemblies, and multiple end products. The system keeps inventory of components and components are assembled into the end-products after information on customer demand is received. Therefore, the overall manufacturing process is a combination of two steps; component procurement or production, and assembly. Assemble-to-order manufacturing companies that aim to operate with a minimum cost and a high customer service level face a challenging task of identifying the best operational strategies for executing these two steps. Only then, they can benefit from the advantages of the assemble-to-order strategy.

Assemble-to-order is very appealing strategy for companies in high-tech, car manufacturing and white goods industry. One common characteristic of these industries is that the component lead times are long. Following the assemble-to-order strategy, the companies can reduce their customer response time by keeping component inventories. In addition, by delaying the final assembly of the end products until the arrival of customer demand, the companies can benefit from pooling component inventories and reduce the cost of offering multiple end products. Assemble-to-order

* Corresponding author.

E-mail address: z.atan@tue.nl (Z. Atan).

Fig. 1. Different customer order penetration points (Olhager, 2012).

systems are difficult to analyze and manage. The following factors contribute to this difficulty: (i) correlation of component demands, (ii) asymmetric component procurement/production lead times and (iii) dependency of the demand fulfillment on the availability of multiple components (Elhafi, Camus, & Craye, 2008). An assemble-to-order system can be viewed as a combination of an assembly system and a distribution system (Song & Zipkin, 2003). The key challenge in assembly systems is the coordination of components and the key challenge in distribution systems is the allocation of components among multiple products. Both are challenges for assemble-to-order systems.

Despite these challenges, in the past years, academics and practitioners have become increasingly interested in analyzing the assemble-to-order systems. The academic literature has increased notably with most of the papers being published in the top journals in the field. Song and Zipkin (2003) review the literature until 2003. The authors acknowledge the progress in development of analytical methods for performance estimation of the assemble-to-order systems. They identify the need for additional research on determination of the optimal policies, development of tractable methods for large-scale systems with time-varying or state-dependent demand and consideration of eventual shifts in supply chain structures and costs (Song & Zipkin, 2003).

The purpose of this paper is to take stock of the literature and provide an overview of the research questions that have been addressed since the review of Song and Zipkin. We aim to provide a comprehensive review to serve as a reference for researchers who work in the field and identify multiple promising future research directions.

The remainder of this paper is organized as follows. We present models for periodic-review and continuous-review systems in Sections 2 and 3, respectively. In Section 4 we provide a summary and in Section 5 we suggest directions for future research.

2. Periodic-review models

In this section, we study ATO models in the periodic-review setting. We divide the stream of literature on periodic-review models into two subcategories depending on the number of periods considered; one-period models (Section 2.1) and multi-period models (Section 2.2).

2.1. One-period models

Multiple researchers studying periodic-review models base their results and insights on single-period analysis. The main motivation is the intractability of the multi-period problem. By concentrating on single-period analysis, they obtain insights that are likely to be valid with some variations for multi-period settings. Another reason is that some problems are single-period problems by nature. For example, rapid changes in technology and ongoing engineering changes can force companies to consider each customer order individually. Therefore, component purchasing decisions need to be made for each individual customer. Furthermore, in engineer-to-order situations each product is unique, and in-

volves substantial engineering of key components, whereby they are unique, too.

In a one-period setting, the manufacturer orders the components only once. The order quantities depend on uncertain but anticipated demand for the end products. After realization of the products' demand, the end products are assembled and delivered to the customers as soon as possible. Components may have different lead times. Therefore, the main problem is the coordination, i.e., synchronization, of the timing and quantity of the orders. We discuss how researchers handle this problem by further dividing the literature on one-period models into two depending on the number of end products; single end product (Section 2.1.1) and multiple end products (Section 2.1.2).

2.1.1. Single end product

In a one-period setting with a single end product, the major decision is the number of components to be ordered and assembled before and after demand realization. One subject that has been studied in particular in this setting is lead time dependent product prices. The decision maker, referred to as manufacturer, knows the demand arrival time and knows the probability distribution of the customer order quantity. All components have positive lead times. The unit price of the product depends on the manufacturer's delivery lead time. The earlier the delivery, the higher the product price, so the manufacturer wants to deliver the products as soon as possible. This translates into a need of ordering the components before the demand is realized.

In this setting, Hsu, Lee, and So (2006) develop an optimization model to determine the optimal number of components that should be ordered before demand is realized. The price for the final product and the component costs depend on the delivery lead times. The authors provide a solution procedure that allows delivery of the full order quantity in multiple shipments (partial-shipment model). They extend their model to the case where partial delivery is allowed with an additional shortage cost. Hsu et al. (2006) show that a change in one component's lead time or cost structure can affect the procurement quantities of other components. In a subsequent and related work, Hsu, Lee, and So (2007) determine the optimal procurement quantities in a setting where the demand has to be met in one shipment (full-shipment model). This extra restriction results in a lower expected profit. Depending on demand uncertainty, the optimal component stocking quantities can be higher or lower than the partial-shipment model. Hsu et al. (2007) also show that longer lead times result in lower profit in both models but the decrease in expected profit is larger under full-shipment model.

Fu, Hsu, and Lee (2006) and Fang, So, and Wang (2008) study similar settings as Hsu et al. (2006) and Hsu et al. (2007). In addition to long and uncertain lead times, Fu et al. (2006) consider limited assembly capacity and the possibility to outsource assembly in case of capacity shortage. Therefore, the manufacturer may not only need to procure components in advance but he may also need to assemble some quantities of the final product before receiving the confirmation of the actual order quantity. The authors develop a profit-maximization model to determine the optimal component procurement and final product inventory decisions. Fang et al. (2008) use a game theoretic approach to explore the use of consignment inventory for coordinating component deliveries. The authors develop an algorithm for determining manufacturer's optimal lead time dependent pricing scheme.

Another way of handling the components' stockout problem is using multiple sourcing channels, which offer different prices and lead times. Yao, Lee, Chew, Hsu, and Jaruphongsa (2013) compare the performance of assemble-to-order systems with single- and dual-channel procurement options. They conclude that when the uncertainty in product demand is high, dual-channel sourcing of-

fers higher economic benefits than single-channel sourcing since the former gives more options to acquire additional components. The size of these benefits depends on how the price of the final product changes as the delivery date changes. If the price drops significantly over time, the manufacturer tends to stock more components before demand is realized. In this case the economic benefit of dual-channel sourcing is not significant. Yao et al. (2013) also discuss the extension of their solution to the problem with multiple sourcing channels.

In the case where the product price does not depend on the delivery time, Xiao, Chen, and Lee (2010b) study the assemble-to-order systems with limited assembly capacity and the option of placing emergency component orders. In their setting, each order has a fixed due date. The authors identify the conditions under which a strategy of assembling the components before demand is realized should be adapted.

As a result, in a one-period setting with a single end product, multiple studies with different modeling assumptions analyze the optimal component procurement decision with lead time dependent end product price. Limited assembly capacity is another dimension considered in this context. The optimal component stocking quantities heavily depend on available shipment modes, lead times and assembly capacity. Since most companies assemble more than one end product, any other extension assuming a single end product can only serve as a starting point for solving problems with multiple end products.

2.1.2. Multiple end products

In assemble-to-order systems with multiple end products, the same components might be required by some end products. The main challenge is the allocation of these common components to different end products. Analyzing the systems with multiple end products is more complicated than analyzing the single end product systems since the manufacturer needs to make both ordering and allocation decisions. Ordering decisions are made before demand realizes while allocation decisions are made after demand realizes.

van Mieghem (2004) studies the allocation problem of an assemble-to-order system with two end products, which can either consist of two product specific components (no-commonality model), or one specific and one common component (pure commonality model). The common component is more expensive than the specific components since it provides risk-pooling benefits to the system. van Mieghem (2004) finds that the pure commonality model is never optimal unless complexity costs are introduced. The results of van Mieghem (2004) are based on the minimization of total holding and shortage costs. Fong, Fu, and Li (2004) obtain similar findings by minimizing the number of shortages subject to a budget constraint. Bernstein, DeCroix, and Wang (2007), Zhang, Ou, and Gilbert (2008) and Chod, Pyke, and Rudi (2010) extend these models by optimizing the component prices.

As stated before, in one-period models the components are ordered once at the beginning of the period. There are exceptions where emergency component orders are allowed. All studies discussed so far assume that the customer demand is satisfied only at the end of the period. Bernstein, DeCroix, and Wang (2011) and Xiao, Chen, and Lee (2010a) relax this assumption by considering a setting where the selling season is divided into K time blocks. After each time block, the manufacturer decides which customer demand of the previous time block to satisfy. The case of $K = 1$ corresponds to the allocation with complete demand information as studied by van Mieghem (2004), whereas $K \rightarrow \infty$ corresponds to the case where allocation decisions are made after each demand arrival. Therefore, with smaller K , the manufacturer knows more about his demand but customers need to wait for longer to get their products. Xiao et al. (2010a) consider the case with two time

blocks and propose a model for optimizing the manufacturer's inventory and production decisions. Bernstein et al. (2011) model customer impatience and determine the factors influencing the optimal number of blocks. The authors conclude that a higher degree of demand aggregation, i.e. small K , benefits the manufacturer the most when demand variability is high, when the common component is expensive and when the demand for low-revenue product is more than that for high-revenue product.

In many real-world assemble-to-order systems, components are first assembled into modules and then modules are assembled into end products. In this case, the manufacturer can keep inventory at the component and module level and perform the final assembly process according to realized demand for the end products. Such a strategy allows product diversity and quick reaction to customer demand (Cheng, Gao, & Shen, 2011). These benefits have triggered researchers to investigate optimal module selection. One such study in a single-period multiple end products setting is by Tsai, Chen, and Lo (2013). The authors develop a two-stage cost minimization model to determine module composition and production volume. The first stage determines the sets of components that can be pre-assembled into modules (module mining) and the second stage finds the optimal combination of modules. Module mining determines which modules are used most frequently. A case study shows that the module composition of the optimal solution largely depends on the assembly costs. Zhou, Lin, and Liu (2007) study a similar problem but they assume that the different variants of pre-assembled modules are known in advance. The authors develop a model to determine the modules to be pre-assembled to minimize the customer utility per cost of implementing the modules.

Similar to Fu et al. (2006), Inman and Schmeling (2003) consider limited assembly capacity but in a multiple end products setting. Their results are based on a case study performed within the automobile industry where each individual product is matched to a customer order. The authors conclude that decoupling orders from physical vehicles can significantly improve performance.

In a recent study Zipkin (2016) models the component allocation problem of an assemble-to-order system with multiple components and multiple end products as an integer linear program. The author shows that for specific system structures, under a condition on the component inventories, the feasible solution set is polymatroid and this enables easy determination of the optimal solution of the integer linear program.

As a result, in a one-period setting with multiple end products, the optimal ordering and allocation decisions depend on components' commonality level and the manufacturer's choice of keeping inventories in the form of components and/or sub-assemblies.

Table 1 summarizes the literature on periodic-review, one period assemble-to-order systems. For all studies discussed in Sections 2.1.1 and 2.1.2 we provide details on the number of components, number of products, number of echelons, allocation policy, backordering or lost sales assumption, component lead times and assembly lead time. The abbreviations D., B and L stand for deterministic, backordering and lost sales, respectively.

2.2. Multi-period models

In a multi-period setting, the manufacturer can place component orders at the beginning of every period and customer demand arrives at the end of every period. End-of-period component inventories and backlogs, and end product backlogs are carried to the next period. Thus unmet end product demand of a given period may be backordered to the subsequent period. Similar to Section 2.1 we divide the literature on multi-period models into two depending on the number of end products; single end product (Section 2.2.1) and multiple end products (Section 2.2.2).

Table 1

Summary of the literature on periodic-review, one period assemble-to-order systems.

Paper	# of comp	# of prod	# of ech	Allocation policy	Backorder (B) or lost sales (L)	Component lead times	Assembly lead time
Fang et al. (2008)	m	1	2	–	B	D.	Zero
Fu et al. (2006)	m	1	2	–	B	D.	D.
Fu, Hsu, and Lee (2009)	m	1	2	–	B	D.	Zero
Hsu et al. (2006)	m	1	2	–	B	D.	Zero
Hsu et al. (2007)	m	1	2	–	B	D.	Zero
Xiao et al. (2010b)	m	1	2	–	L	D.	D.
Yao et al. (2013)	m	1	2	–	B	D.	Zero
Bernstein et al. (2007)	3	2	2	Priority rule	L	–	–
Bernstein et al. (2011)	3	2	2	Other	L	–	–
Chod et al. (2010)	m	n	2	–	B	–	–
Fong et al. (2004)	3 or 4	2	2	General	L	–	–
Inman and Schmeling (2003)	m	n	> 2	Other	–	–	General
Lee, Chew, and Manikam (2006)	m	n	2	Other	L	–	–
Tsai et al. (2013)	m	n	> 2	–	–	–	–
van Mieghem (2004)	5	2	2	Priority rule	L	–	–
Xiao et al. (2010a)	3	2	2	Rationing	L	–	–
Zhang et al. (2008)	3	2	2	Priority rule	L	–	–
Zipkin (2016)	m	n	2	–	B/L	D.	Zero

2.2.1. Single end product

In the case where the manufacturer produces only one end product, the major decision is related to component order synchronization. The problem of component allocation does not exist.

Karaarslan, Kiesmüller, and de Kok (2013) study the component replenishment decisions of a manufacturer who produces a single product by assembling two components. One component has a high holding cost, long lead time and short review period and the other has a lower holding cost with short lead time and long review period. The authors compare a pure base-stock policy with a so-called balanced base-stock policy, and derive the optimality conditions. The balanced-base stock policy synchronizes the echelon-inventory position of the short-lead-time component with the inventory position of the long-lead-time component by ordering up to the long-lead-time component's coverage of future demand over the short lead time (plus review period). Karaarslan et al. (2013) conclude that the balanced base-stock policy outperforms the pure base-stock policy under low service levels and high demand uncertainty.

Pang, Chen, and Feng (2012) investigate a setting in which the end product consists of only one component. This component may have a different price in each period. Furthermore, the demand depends on the product price. In every time period, the price of the component and the ordering quantity have to be determined. This formulation can be extended to a setting in which the product consists of multiple components so it results in an assemble-to-order system with price sensitive demand.

There are several situations in which the manufacturer's production process is influenced by external factors. One example is supply disruptions. When the manufacturer's supply process is disrupted, he cannot receive any components through the disrupted supply process until the disruption ends. The manufacturer needs to take a reactive action. Shao and Dong (2012) study the disruption problem of a manufacturer who purchases two components from a supplier and assembles them to satisfy his customer demand. The authors consider multiple recovery strategies and show that a policy which combines backordering, backup sourcing and compensation for late delivery performs the best.

Another external factor to influence the manufacturers production process is technology innovation. Many high-tech companies assemble to order and they strive to rapidly improve the performance of their products by innovating their components. This results in a complicated and dynamic planning problem faced by many high-tech companies. Xu and Li (2007) study this problem

of a manufacturer who assembles an end product from multiple components. For each component, there are two coexisting technologies. The manufacturer needs to make technology and inventory decisions. The authors investigate two coordination schemes, one where the decisions are sequentially made (strategic level), and another where decisions are jointly made (operational level). The authors show that it is often adequate to only consider the strategic level coordination but the operational level coordination becomes more dominant when demand variability is high.

We note that the recent literature on multi-period models with single end product is rather limited. This may be due to the fact that already in Rosling (1989) the optimal policy for constant component lead times has been characterized for a multi-item multi-echelon assembly system. The studies discussed above consider different dimensions, e.g., supply disruptions and technology innovation, of the same problem. Extending the results of Rosling (1989) to stochastic lead times is still an open problem.

2.2.2. Multiple end products

In this section, we summarize the studies that analyze assemble-to-order systems with multiple end products and consider a finite or infinite time horizon consisting of multiple periods. As in Section 2.2.1, the manufacturer has two major decisions to make; one related to replenishment quantities of the components and the other related to the allocation of the common components to multiple end products.

There are multiple studies which concentrate on the replenishment decision and make a specific assumption regarding the allocation of the components. The most dominant principle is the first-come-first-served (FCFS) rule. Huang and de Kok (2015) study an assemble-to-order system with linear holding and backordering costs, installation stock replenishment policy and a FCFS allocation rule. The authors show that the FCFS allocation rule decouples the problem of optimal component allocation over time into deterministic period-to-period optimal component allocation problems.

Despite its popularity, the FCFS allocation rule does not reflect the fact that end products may have different service level requirements and different costs associated with backorders. It is known that the FCFS rule is not necessarily optimal (Song & Zipkin, 2003). Therefore, there is a need for non-FCFS allocation rules. In fact, Akçay and Xu (2004) show that optimizing the allocation rule is as important as optimizing the inventory replenishment policy. The authors assume independent base-stock replenishment policies for the components and formulate a two-stage stochastic program to

determine the optimal base-stock policy and the optimal component allocation policy. They show that the component allocation problem is NP-hard and propose an order-based component allocation rule. This rule commits a component to an order only if it leads to the fulfillment of the order within the committed time window. Akçay and Xu (2004) show that their order-based component allocation rule outperforms the component-based allocation rules, where component allocation decisions are made independently across different components.

Multiple authors study other component allocation rules. For example, Mohebbi and Choobineh (2005) consider a rationing rule which allocates components to end products with the smallest number of components first. In addition, even if there are outstanding orders from the previous periods, the last period's demand is satisfied first. Only then, the orders from previous periods are satisfied in a FCFS fashion. The same allocation rule is used in Baker, Magazine, and Nuttle (1986). Mohebbi and Choobineh (2005) study the effect of component commonality on the performance of the assemble-to-order systems. Through an extensive simulation study they show that increasing component commonality works better in systems with high uncertainty in both end products' demand and components' replenishment lead times. In addition, they show that the impact of increasing commonality on reducing the average number of end product backorders or reducing the average component inventory levels is not significant.

Huang, Jin, Huang, and Qiu (2014) studies two non-FCFS component allocation policies. The first one is similar to the policy introduced in Mohebbi and Choobineh (2005). The second policy is a priority based rule. Within a time window, demands of some products have higher priorities than other products. However, demands from an earlier time period are always satisfied first. Huang et al. (2014) concludes that both rules not only outperform FCFS allocation rule but they also address differences in customer service requirements.

Both Akçay and Xu (2004) and Huang et al. (2014) assume backordering, which implies that all customer demands are eventually satisfied. Gühlich, Fleischmann, and Stolletz (2015) study the demand management decision of a manufacturer who has limited assembly capacity. For each incoming order, the manufacturer has to decide whether to accept it and for each accepted order he has to quote a due date. The authors use bid prices to check if accepting an order yields a feasible schedule with respect to component availability and assembly capacity. Gühlich et al. (2015) show that their approach performs close to the post-optimal solution, which is the optimal solution if all demands would be known in advance. In addition, they conclude that the assembly capacity constraint is more important than the component availability constraints.

Many manufacturing companies that adopt an assemble-to-order strategy sell substitutable products. When end products have similar features but small differences in some of the components, customers might base their purchasing decisions on end products' prices. Hence, in addition to component replenishment and allocation decisions, companies selling substitutable products face a challenging pricing decision. Oh, Sourirajan, and Ettl (2014) study the problem of optimizing inventory replenishment, pricing and component allocation decisions in an assemble-to-order system. The authors propose a heuristic policy that decouples these three decisions. The heuristic policy gives the optimal solution when demands do not decrease over time.

An assemble-to-order strategy works well when the demands for multiple end products sharing common components have high variance. Assemble-in-advance strategy reduces customer waiting time. Companies can enjoy the benefits of both strategies by employing them simultaneously. Eynan and Rosenblatt (2007) consider a manufacturer who employs a combination of both strategies and conclude that the combination results in higher profit.

The authors show that as component commonality increases, the optimal number of products that are pre-assembled decreases.

Multiple studies, including Plambeck and Ward (2006), Loveland, Monkman, and Morrice (2007), Monkman, Morrice, and Bard (2008), Tsai and Wang (2009) and Chen and Dong (2014), focus on production planning decisions in assemble-to-order manufacturing environment. All studies argue that multiple factors influence these complex decisions and they either propose heuristic approaches or exact solutions for relatively simple systems.

As discussed in Eynan and Rosenblatt (2007), the performance of assemble-to-order strategy can be enhanced if it is implemented in combination with other strategies. Depending on the manufacturing environment, it might also be better or practical to consider slight variations of the assemble-to-order strategy. Some of these strategies are the assemble-in-advance strategy (Eynan & Rosenblatt, 2007), the configure-to-order strategy (Cheng, Ettl, Lin, & Yao, 2002) and make-to-forecast strategy (Meredith & Akinc, 2007). We do not discuss these strategies since the focus of this literature review is the assemble-to-order strategy.

As a result, in a multi-period setting with multiple end products, researchers address the differences in customer service requirements. They conclude that the commonly employed FCFS policy is not optimal and, therefore, propose multiple alternative allocation policies. The optimal allocation policy is unknown, it is case-dependent and difficult to characterize. Hence, more structural insights on allocation policies are needed. Another collective understanding is related to the component commonality. It is concluded that increasing component commonality works in systems with (i) high demand uncertainty in end products' demand and (ii) high uncertainty in components' replenishment lead times.

Table 2 summarizes the literature on periodic-review, multi-period assemble-to-order systems. For all studies discussed in Sections 2.2.1 and 2.2.2 we provide details on the number of components, number of products, inventory and allocation policies, backordering or lost sales assumption, component lead times and assembly lead time. The abbreviation ATP stands for available-to-promise.

3. Continuous-review models

In this section, we study assemble-to-order models in a continuous-review setting. Different from Section 2, the manufacturer monitors his system continuously and, depending on the status of the system, can give immediate replenishment and assembly decisions. We divide the stream of literature on continuous-review models into two subcategories depending on the number of end products. We study the single end product models in Section 3.1 and a broader stream of literature on continuous-review multiple end product models in Section 3.2.

3.1. Single end product

The main challenge in continuous-review models with a single end product is component order synchronization. In this section, we explain how researchers consider other dimensions of the problem and tackle the challenge. Most models in the assemble-to-order literature assume that demands arising from different sources are handled similarly. In practice, however, for a single product, different customers may have different service level requirements or may be of different importance to the manufacturer. Therefore, it might be appropriate to segment customers into several classes and use different policies in satisfying their demands. Hence, one dimension studied by multiple researchers is related to differences in satisfying customer orders.

Table 2

Summary of the literature on periodic-review, multi-period assemble-to-order systems.

Paper	# of comp	# of prod	Replenishment policy	Allocation policy	(B) or (L)	Component lead times	Assembly lead time
Karaarslan et al. (2013)	2	1	Base-stock or balanced base-stock	–	B	D.	Zero
Pang et al. (2012)	1	1	Other	–	B	D.	Zero
Shao and Dong (2012)	1	1	Order driven	–	B	General	Zero
Xu and Li (2007)	m	1	Balanced base-stock	–	L	Zero	Zero
Akçay and Xu (2004)	m	n	Base-stock	Other	B	D.	Zero
Chen and Dong (2014)	m	n	Other	ATP	B	D.	D.
Eynan and Rosenblatt (2007)	3	2	Other	Priority rule	L	Zero	Zero
Gühlich et al. (2015)	m	n	–	ATP	B and L	–	D.
Huang et al. (2014)	m	n	Base-stock	Other	B	D.	Zero
Huang and de Kok (2015)	m	n	Installation stock	FCFS	B	D.	Zero
Loveland et al. (2007)	–	n	–	–	B	–	D.
Mohebbi and Choobineh (2005)	m	3	Lot for lot	Other	B	General	D.
Monkman et al. (2008)	–	n	–	–	B	–	D.
Oh et al. (2014)	m	n	Base-stock	Other	B	One period	Zero
Papadakis (2003)	m	n	–	–	–	–	–
Plambeck and Ward (2006)	m	n	–	Other	B	–	General
Tsai and Wang (2009)	m	n	–	ATP	L	–	D.

Problems involving several demand classes have been studied extensively in the supply chain and inventory management literature. Multiple authors study the assemble-to-order strategy with multiple demand classes. Benjaafar and Elhafsi (2006) consider an assemble-to-order system with multiple components and a single end product. To satisfy a customer order, all components must be available. Otherwise, the order is lost. Benjaafar and Elhafsi (2006) assume that customers can be categorized according to their shortage costs. The manufacturer aims to minimize the sum of component holding and shortage costs by optimizing his production and order acceptance decisions. The manufacturer might want to reject a demand from a class to save the available components for potential demands from higher priority customer classes. Under this setting, Benjaafar and Elhafsi (2006) find that the optimal production and order acceptance policies are state-dependent base-stock and multi-level state-dependent rationing policies, respectively.

In a subsequent study (Elhafsi, 2009) extends the results of Benjaafar and Elhafsi (2006) by considering compound Poisson demands. Therefore, when an order arrives the manufacturer has to decide what proportion of the order to satisfy. The optimal production and inventory allocation policies remain the same as in Benjaafar and Elhafsi (2006). Elhafsi (2009) concludes that the optimal rationing policy provides substantial benefits compared to the traditional FCFS allocation policy. Elhafsi, Zhi, Camus, and Craye (2015) study a similar problem with two customer classes and assume that customer demands occur not only for the end product but also for individual components. The authors obtain similar results as Elhafsi (2009) for the optimal production and allocation policies and show that the optimal rationing policy is not static but depends on the inventory levels of components.

In a related work Elhafsi and Hamouda (2015) study an assemble-to-order manufacturing system, where in addition to the end product, components are also available for sale. Assuming exponential component production times and independent Poisson demands for the end product and the individual components, the authors show the optimality of the state-dependent base-stock component production policy and the state-dependent rationing policy. They propose efficient heuristic policies, which ignore state dependency of the threshold levels.

Pricing is a commonly utilized strategy for demand and inventory management. In an assemble-to-order setting, the manufacturer can affect the component inventory levels by changing the

price of the end product. When the inventory of components is too high, he can reduce the selling price of the end product and vice versa. Feng, Ou, and Pang (2008) study such a problem in an assemble-to-order environment with stochastic component production processes. The manufacturer aims to maximize his total profit by optimally controlling component production and the end product's price. For the end product's price, Feng et al. (2008) consider several discrete levels, with each level generating a different demand rate. The authors prove that the optimal control for each component follows a base-stock policy, with the base-stock level depending on the inventories of other components. The optimal pricing policy is a threshold policy with the thresholds affected by all components' inventory levels. The same pricing policy is proved to be optimal by Kebli and Feng (2012) in a setting with a more general stockout cost function.

In assemble-to-order systems, each component supply process has its own production lead time. With regard to the nature of component production lead times, researchers have considered two types of lead times: exogenous and endogenous lead times. In the former, production lead time is not affected by the number of outstanding orders and it is load-independent. However, in the latter, production lead time depends on the number of outstanding orders and it is load-dependent (Benjaafar & Elhafsi, 2006; Cheng et al., 2011; Elhafsi, 2009; Elhafsi et al., 2015). It is obvious that management of a load-dependent production system is significantly more complicated than management of a load-independent production system, since the former needs investigation of pure inventory systems, while the latter deals with an integrated production-inventory system. However, under the assumption of exponential processing time for each component, it turns out to be possible to characterize the optimal policy structure. Clearly, the memorylessness of the exponential distribution plays a key role, as it greatly simplifies the state definition of the underlying Markov decision process. As stated above, the optimal policy combines state-dependent base stock policies and critical level rationing policies. This motivates the use of base stock policies in more general settings. Indeed, in the single end product setting, all authors have considered a base-stock or (S-1, S) policy (see Table 3) as replenishment policy.

In addition to component lead times, it is also important to study the customer lead time, i.e. the time needed to satisfy customer orders. Assuming base-stock replenishment policy for all components, Ko, Choi, and Seo (2011) propose an approximation method to determine the distribution of customer lead time.

Table 3

Summary of the literature on continuous-review, single end product assemble-to-order systems.

Paper lead time	Replenishment policy	Allocation policy	Backorder (B) or (L)	Component lead times
Benjaafar and Elhafsi (2006)	SD base-stock	Rationing	L	Exp.
Cheng et al. (2011)	SD base-stock	Rationing	B and L	Exp.
Elhafsi (2009)	SD base-stock	SD rationing	L	Exp.
Elhafsi et al. (2015)	SD base-stock	SD rationing	L	Exp.
Elhafsi and Hamouda (2015)	SD base-stock	SD rationing	B	Exp.
Feng et al. (2008)	SD base-stock	FCFS	B	Exp.
Kebli and Feng (2012)	SD base-stock	FCFS	B	Exp.
Ko et al. (2011)	Base-stock	–	B	Exp.

Another complication affecting component lead times is unpredictable machine breakdowns. While most researches consider failure-free machines in the component supply process, Cheng et al. (2011) consider failure-prone machines, where each component is produced and replenished by a dedicated machine that is affected by unpredictable breakdowns. The authors conclude that a machine's state not only has an impact on the production and allocation policies of its own component, but also influences policies related to other components. Cheng et al. (2011) show that a component's optimal replenishment policy is a state-dependent base-stock policy with the base-stock level non-decreasing in the inventory levels of the other components and the states of the other machines.

As a summary, an important result for continuous-review single end product models with multiple demand classes is the optimality of state-dependent base-stock production/replenishment policy and the optimality of state-dependent rationing order acceptance policy. When the end product price is also a decision variable, the optimal policy is a state-dependent threshold policy with the threshold affected by all components' inventory levels. In addition, multiple authors analyze the component lead times and prove the optimality of state-dependent base-stock policy. Similar to periodic-review models with single end product, it is possible to study multiple different variants of the continuous-review models with single end product by adding complexities but for the practical purposes it suffices to know what replenishment policies should be used. The state-dependent base-stock policies emerge for most systems but it depends on the particular demand and supply process to what extend these policies can be applied.

Table 3 summarizes the literature on continuous-review, single end product assemble-to-order systems. For all studies discussed in Section 3.1 we provide details on replenishment and allocation policies, backordering or lost sales assumption and component lead times. The assembly lead time is zero in all these studies. The abbreviations SD and Exp. stand for state-dependent and exponential, respectively.

3.2. Multiple end products

An enormous body of literature in continuous-review is related to the multiple end product setting. This is why we categorize the studies in this setting into four sections; component commonality, performance metrics, optimal control policies and approximation methods.

3.2.1. Component commonality

Assemble-to-order systems with multiple end products can be considered as an integration of distribution and assembly systems (Song & Zipkin, 2003). These are far more complex than systems with a single end product, since they must address both optimal component allocation and component inventory replenishment policies. In general, there is no hope for finding the optimal policy for systems with multiple components and end-products

due to the curses of dimensionality and lack of special properties of the cost-to-go-function. Fortunately, special Bill of Material structures combined with assumptions on the demand process and supply process allow for characterizing the optimal policy. This motivates researchers to categorize these systems according to the configuration of the system which is influenced by the commonality degree of the components, the number of components and end products. The most common configurations that have been studied in the literature are (Lu, Song, & Zhao, 2010; Nadar, Akan, & Scheller-wolf, 2014):

1. *N*-system: consists of two components and two end products (Lu, Song, & Zhang, 2015; Lu et al., 2010). One end product is assembled from both components and the other end product is manufactured from one of the components.
2. *M*-system: consists of two components and three end products (Lu & Song, 2005; Nadar et al., 2014). One end product is assembled from both components. Other end products are manufactured from one of the components.
3. *W*-system: consists of three components and two end products (Dogru, Reiman, & Wang, 2010; Lu et al., 2010; Shao & Ji, 2009). Each end product consists of one common component and one product specific component.
4. Nested system: consists of multiple components and multiple end products (Elhafsi et al., 2008). The set of components used in manufacturing of one end product is a subset of the set of components needed for the next larger end product.

Component commonality is a differentiating factor in these systems. The systems are named after the shape of each structure, as seen in Fig. 2.

As mentioned before, in multiple end product assemble-to-order systems, it is likely to have common components for different end products. Component commonality is one of the fundamental conditions for mass customization. It enables product diversity at low cost. The value of component commonality and its sensitivity to system parameters in assemble-to-order systems is studied by Song and Zhao (2009). Under the regular first-in-first-out (FIFO) allocation policy component demands are fulfilled in the same sequence as they occur. Song and Zhao (2009) propose a modified FIFO allocation policy under which product demand is fulfilled following the FIFO rule as long as required components are available. If some of the components are not available, the product demand is assigned to the last position in the backorder list. The authors acknowledge the benefits of component commonality under both allocation rules and argue that its value depends heavily on the component costs and lead times. They conclude that the inventory savings are more significant under the modified FIFO allocation policy and the performance gap between the regular and modified FIFO policies depends on the fill rate and component lead times.

Shi and Zhao (2014) consider a similar problem under different assumptions. They study the value of component commonality in assemble-to-order systems under no-holdback (NHB) allocation

Fig. 2. Configurations of assemble-to-order systems (Nadar et al., 2014).

policies. Under such a policy, a product demand is backordered if and only if at least one of its required components is out of stock. Shi and Zhao (2014) prove that under any no-holdback rule, as the degree of commonality increases, the total product backorder and on-hand component inventory decrease.

One of the implications of component commonality is correlation between demand for different components. Lu and Song (2005) study the role of demand correlation in an assemble-to-order system by comparing the solution of an order-based formulation including demand correlation to that of a component-based formulation, in which the correlation is ignored. Lu and Song (2005) demonstrate that ignoring demand correlation may result in significant cost increase. Shao and Ji (2009) study the pricing and sourcing decisions of an assemble-to-order system consisting of two substitutable products and three components purchased from different suppliers. The authors conclude that the system performance becomes worse if dedicated components are sourced from a single supplier and the common component is sourced from another independent supplier.

As a conclusion, the value of component commonality in assemble-to-order systems depends on multiple factors including the component costs, lead times and sourcing options. Although it is unquestionable, the real value of component commonality is difficult to quantify. More rigorous research is needed.

3.2.2. Performance metrics

One stream of literature in multiple end product setting introduces performance metrics for assemble-to-order systems. This stream of research is motivated by the intractability of the optimal policy. Determining expressions for the performance metrics of an assemble-to-order system under given assumptions is an important first step.

Zhao (2009) studies an assemble-to-order system with compound Poisson demand, where a customer may order more than one unit of an end product. Because each end product is assembled from several components, it may not always be possible to fulfill the entire demand immediately and customers would either receive each unit of product as soon as it becomes available (split orders) or wait to receive all units at the same time (non-split orders). Zhao (2009) considers delivery lead time and order-based fill rate as performance metrics and derives their exact expressions under both split and non-split order fulfillment.

Similar to Zhao (2009), Lu, Song, and Yao (2005) study a system with compound Poisson product demands. The component lead times are random and inventory of each component is controlled by a base-stock policy. As a performance measure, Lu et al. (2005) focus on the expected backorders for each product. The authors study the optimal allocation of a limited budget among component inventories to minimize a weighted average of backorders over all products. Their solution approach is based on developing approximations and bounds for the expected number of backorders.

Additional to positive customer demand, negative customer demand is common in situations, where the firms may have special

return policies to provide a higher service level. In an assemble-to-order environment the returned end products can be disassembled and the components can be returned to the component warehouse. The negative demand imposes additional complexities. DeCroix, Song, and Zipkin (2009) consider such a system facing both positive and negative independent Poisson demand for both end product and components. Assuming a base-stock policy for each component's replenishment process, they provide approximate expressions for multiple performance measures, such as the immediate fill rate, fill rate within a time window, and average backorders. In addition, they propose a method to calculate a near-optimal base-stock policy.

In real-world assemble-to-order systems, where end products consist of many components, customers might view some of the components as "key" and others as "non-key" components. Iravani et al. (2003) study this case and assume that a customer demand is lost if a key component is not available (selective customer) or he accepts substitution for unavailable components (flexible customer). Iravani et al. (2003) use customer satisfaction as a performance measure and conclude that substitution improves the overall service but might result in profit loss.

A response-time based order fill rate is another performance measure. Assuming compound Poisson demands for the end products and base-stock policies to control component inventories, Lu, Song, and Yao (2003) derive the exact joint distribution of end product outstanding orders and develop approximations and bounds for the order fill rates. Lu (2008) generalizes the results in Lu et al. (2003) by relaxing the assumption of Poisson demand and allows the demand arrival processes to be general renewal processes. The author develops approximations for key performance measures such as average inventory and order fill rate. For a capacitated assemble-to-order system with Poisson demand and backordering, Fu, Hsu, and Lee (2011) also propose approximate methods for obtaining bounds on similar performance metrics.

The difficulty of exact evaluation of any performance metric of complex assemble-to-order systems is undeniable. This is why the studies outlined above rely on approximate procedures. Feng, Liu, and Wan (2012) consider an order-based backorder level as the performance measure and identify a necessary and sufficient condition to evaluate this measure. The condition is in the form of simultaneous linear Diophantine equations. This shows the underlying combinatorial complexity of analysis of assemble-to-order systems.

Dayanik, Song, and Hu (2003) identify the same difficulties in evaluating complex assemble-to-order systems with multiple end products. A component's fill rate depends on demands for all end products which include that component. Thus, measuring the fill rate is computationally demanding due to the involvement of multivariate probability distributions. To overcome this problem, Dayanik et al. (2003) consider a correlated $M/M/1/N$ queueing system for the supply system of each component and develop bounds to provide computationally efficient performance estimates for order fill rates in the system. Bušić, Vliegen, and Scheller-wolf (2012) provide a new method for obtaining bounds

Table 4

Summary of the literature on continuous-review, multiple end products assemble-to-order systems.

Paper lead time	Replenishment policy	Allocation policy	Backorder (B) or (L)	Component lead times
Bušić et al. (2012)	Base-stock	FCFS	B and L	Exp.
Dayanik et al. (2003)	Base-stock	FCFS	L and B	Exp.
DeCroix et al. (2009)	Base-stock	FCFS	B	D
Dogru et al. (2010)	Base-stock	PBC	B	D
Dogru et al. (2017)	–	–	B	D
Elhafsi et al. (2008)	SD base-stock	SD rationing	L	Exp.
Feng et al. (2012)	Base-stock	–	B	D
Fu et al. (2011)	Base-stock	FCFS	B	Exp.
Gao et al. (2010)	Base-stock	FCFS	B and L	Exp.
Hoen et al. (2011)	Base-stock	–	L	D
Hong and Yang (2012)	Base-stock	–	L	Normal
Huang et al. (2014)	Batch-ordering and JIT	–	L	D and zero
Iravani et al. (2003)	Base-stock	–	L	Exp.
Iravani et al. (2004)	Base-stock	FCFS	L	Exp.
Lu (2008)	Base-stock	FCFS	B	General
Lu and Song (2005)	Base-stock	FCFS	B	General and D
Lu et al. (2003)	Base-stock	FCFS	B	General
Lu et al. (2005)	Base-stock	FCFS	B	Exp.
Lu et al. (2010)	Base-stock	NHB	B	D
Lu et al. (2015)	Coordinated base-stock	NHB	B	General
Nadar et al. (2014)	LD base-stock	LD rationing	L	Exp.
Nadar et al. (2016)	LD base-stock	LD rationing	L	Exp.
Plambeck (2008)	Threshold	FCFS	L	D
Plambeck and Ward (2007)	Base-stock	FCFS	L	General
Reiman and Wang (2012)	Base-stock	–	B	D
Reiman and Wang (2015)	Base-stock	Backorder target	B	D
Reiman et al. (2016)	Base-stock	Backorder target	B	D
Shao and Ji (2009)	–	–	–	D
Shi and Zhao (2014)	Base-stock	NHB	B	D
Song and Zhao (2009)	Base-stock	FIFO/MFIFO	B	D
van Jaarsveld and Scheller-Wolf (2015)	Base-stock	FCFS	B	D
Wan and Wang (2015)	–	Backorder target	B	D
Zhao (2009)	Batch-ordering	FCFS	B	General
Zhao and Simchi-Levi (2006)	Base-stock and batch-ordering	FCFS	B	General
Zhou and Chao (2012)	Base-stock	FCFS	B	D/General

for Markov chains. For illustration of their method, they apply it to an assemble-to-order system and study an out-of-stock situation with three possibilities, namely; backordering, fulfilled partly and lost fully.

Another complication contributing to difficulty of analyzing assemble-to-order systems is the unreliability of component production lines. Gao, Shen, and Cheng (2010) study such a system where the demand for each end product is a Poisson process and component inventory levels are controlled by a base-stock policy. The authors derive the exact joint distribution of on-order inventories and use it to calculate performance metrics like order-based and component-based fill rates.

A decomposition approach, which enables performance evaluation, is proposed by Zhao and Simchi-Levi (2006). The authors analyze an assemble-to-order system with stochastic and sequential component lead times. They consider two types of component replenishment policies; a base-stock policy and a batch-ordering policy. Under the former policy, Zhao and Simchi-Levi (2006) show that the system can be decomposed into multiple single-product systems with each subsystem corresponding to one product. For both replenishment policies, the authors develop numerical methods for performance evaluation.

All studies mentioned in this section acknowledge the difficulty of exact evaluation of any performance metric of complex assemble-to-order systems. After making assumptions on component replenishment policies, researchers consider delivery lead time, expected backorders, order-based immediate fill rate, order-based will rate within a time window and a response-time based order fill rate as the performance metrics. In addition to exact evaluations, they propose approximate methods for obtaining bounds.

Due to intractability of optimal policies, we expect more and more studies to emerge with an objective of evaluating performance metrics for complex assemble-to-order systems. These studies will serve as the first step towards identification of optimal component replenishment and allocation policies.

3.2.3. Optimal control policies

An optimal control policy of assemble-to-order systems with multiple end products requires two major decisions; the first one is the replenishment policy decision of the components and the second one is the allocation policy that decides which end product(s) to assemble. In the continuous-review setting the majority of authors have considered a base-stock replenishment policy and proposed various allocation policies (refer to Table 4). The optimal replenishment and allocation policies are not known for general assemble-to-order systems. However, there exist multiple studies, which make specific assumptions and succeed in partially or fully characterizing the optimal replenishment and/or allocation policies. In this section, we review these studies.

Although they are very popular in practice, assemble-to-order systems are difficult to analyze. As stated before, one difficulty is the correlated nature of component demands. This results in a need for multidimensional control. Plambeck and Ward (2007) prove that it is possible to separate this difficult control problem into single-item inventory control problems. They consider a two-echelon assemble-to-order system with product specific target lead time and assume that unavailable components can be expedited. Three decisions are studied; assembly sequencing orders, component production and component expediting. According to their separation result, under an optimal assembly sequencing

policy, the optimal production and expediting policy for each component is independent of other components. In a subsequent study, [Plambeck \(2008\)](#) consider a two-echelon assemble-to-order system with deterministic component transportation times. Assuming a fixed and variable unit transportation costs, the author develops a model to minimize expected discounted costs for production, transportation and lost sales. She shows the asymptotic optimality of a simple threshold policy with independent control of each component for large end product demand rates and a small discount rate.

Another asymptotic optimality result for a two-echelon assemble-to-order system with identical lead times and a general bill of materials is obtained by [Reiman and Wang \(2015\)](#). They formulate the problem as a two-stage stochastic linear program with complete recourse. Replenishment and allocation decisions are considered as first and second stage decisions, respectively. Using a base-stock replenishment policy, [Reiman and Wang \(2015\)](#) prove the asymptotic optimality of an allocation policy which is based on tracking a backordering target. This result holds for *W*-systems and any assemble-to-order systems with identical component lead times. Allocation policy suggested by [Reiman and Wang \(2015\)](#) requires reservation of components for future high-value demands. [Wan and Wang \(2015\)](#) prove that for many systems, any policy that does not reserve components cannot be asymptotically optimal. [Reiman, Wan, and Wang \(2016\)](#) study a similar assemble-to-order system with two-echelons and a general bill of materials structure. However, they allow lead times to be nonidentical. [Reiman et al. \(2016\)](#) prove that the combination of the allocation policy used by [Reiman and Wang \(2015\)](#) and the independent base-stock replenishment policies is asymptotically optimal as the component lead times grow while their differences grow at a slower rate.

The simplest of the assemble-to-order configurations is the *N*-system (refer to [Section 3.2.1](#)). It consists of two components and two end products. For an *N*-system with general component lead times and a state-independent base-stock replenishment policy, [Lu et al. \(2010\)](#) show that a no-holdback allocation rule is optimal among all allocation rules. As defined before, a no-holdback allocation rule allocates a component to a product demand only if such an allocation can lead to the fulfillment of that demand. [Lu et al. \(2015\)](#) study the same system with general component lead times and back-ordering. Assuming a certain symmetric cost structure, the authors prove the optimality of coordinated base-stock policies and no-holdback allocation rules. Under a coordinated base-stock policy, the inventory of the component with a longer lead time is controlled using a standard base-stock policy, while the inventory of the component with a shorter lead time is adjusted according to demand realizations.

A *W*-system with backordering and identical component lead times is studied by [Dogru et al. \(2010\)](#). The authors prove the optimality of a base-stock replenishment policy. They proposed a simple allocation policy called priority-based backorder clearing rule (PBC) and demonstrate that this policy achieves the optimal solution when a balanced capacity condition holds and when both end products have the same unit holding costs. [Lu et al. \(2010\)](#) obtain a similar result for *W*-systems with general component lead times and a base-stock replenishment policy. Assuming a certain symmetric cost structure, they show that no-holdback (NHB) component allocation rules are optimal. [Reiman and Wang \(2012\)](#) generalize the results of [Dogru et al. \(2010\)](#) to *W*-systems with general deterministic component lead times. They present a set of sufficient conditions under which the replenishment and allocation policies achieve the lower bound on the long-run average inventory cost.

A generalized version of an *M*-system with batch ordering, random component lead times and lost sales is studied by [Nadar et al. \(2014\)](#). Under a mild condition on batch component sizes, the au-

thors characterize the optimality of a lattice-dependent base-stock replenishment policy and a lattice-dependent rationing allocation policies.

In a recent study [Dogru, Reiman, and Wang \(2017\)](#) introduces a mechanism that uses two stochastic programs, one-period assemble-to-order model ([Zipkin, 2016](#)) and its relaxation, to determine control policies for dynamic assemble-to-order systems. They introduce a family of assemble-to-order systems, called chained-BOM. The *M*-system is the simplest multi-product system of this family. For assemble-to-order systems within this family, the authors assume identical lead times and show that stochastic programming allows efficient determination of the optimal control policies. For the *M*-systems, [Dogru et al. \(2017\)](#) show that the stochastic programs can be solved as a one-stage optimization problem. The authors conclude that one big advantage of stochastic programming over alternative approaches is that it achieves asymptotic optimality.

[Elhafsi et al. \(2008\)](#) study an assemble-to-order system with multiple components assembled into multiple end products using a nested product design ([Section 3.2.1](#)). Each component is produced in a separate facility with finite production rate and exponentially distributed production time. Demand for each end product is a Poisson process. The demand can be either satisfied or rejected. The system incurs holding cost for each component and lost sales cost for unsatisfied or rejected end product demands. The authors prove the optimality of state-dependent base-stock and state-dependent, multi-level rationing policies. The optimal base-stock and rationing levels depend on the component inventory levels.

As evident from the studies discussed in this section, considerable progress on identification of optimal policies for specific assemble-to-order systems has been made. Insights on the characteristics of optimal inventory replenishment policies and optimal component allocation policies are provided for *N*-, *M*-, and *W*-systems under various assumptions on cost parameters and lead times. The application of stochastic programming has not only led to solution procedures for large-scale systems, but also to the development of new policies that are optimal for special assemble-to-order systems and asymptotically optimal for a wider class of systems. Since there is no hope for finding optimal policies for realistic assemble-to-order systems, a promising avenue for further research is the identification of specific properties of optimal policies within a class of policies. Developing generally applicable policies that can be compared against other policies is the next best the operations research and operations management community can provide.

3.2.4. Approximation methods

As the previous section suggests, the optimal results on assemble-to-order systems exist only for simple configurations. The main reason is the curse of dimensionality of existing solution procedures. There are multiple asymptotic optimality results for the two-echelon assemble-to-order systems with general bill-of-material structure but these also require specific assumptions. Although optimal solutions are preferable, many researchers acknowledge the benefits of good approximations. In this section, we review the studies on approximation methods to analyze large scale assemble-to-order systems. However, in most of these studies no performance guarantees in relation to the optimal policy are provided.

[Iravani, Luangkesorn, and Simchi-Levi \(2004\)](#) consider an assemble-to-order system in which the components are produced in batches. They model the component production processes as a system of parallel queues and assume limited queue space. [Iravani et al. \(2004\)](#) introduce an algorithm to decompose the system with dependent parallel queues into individual independent queues and estimate the performance of each individual queue. They use the

same performance metrics as Iravani et al. (2003). The authors show that their decomposition algorithm is accurate and insensitive to problem size. Another decomposition result is by Hoen, Güllü, van Houtum, and Vliegen (2011). They study an assemble-to-order system with Poisson customer demands and a base-stock replenishment policy. The manufacturer places emergency shipment requests for missing components that are not in stock as a demand for an end product requiring these components arrive. Although the customer demand is not lost since the end product is eventually delivered, the demand for the components supplied through emergency shipments are considered lost (partial order service). Hoen et al. (2011) show that this system can be decomposed into subsystems and develop an approximation to calculate the order fill rate, i.e., the percentage of demands for which all requested components are available from stock.

Zhou and Chao (2012) also provide an approximation to calculate the order fill rate for an assemble-to-order system with Poisson end product demands, random component replenishment lead times and a base-stock component replenishment policy. The error bound of the approximation gets smaller as the variability of the component replenishment lead times increase. Their approximation performs well even when the component demands are highly correlated.

Developing computationally efficient solution methodologies for assemble-to-order systems with many components and end products is challenging. Horng and Yang (2012), Huang et al. (2014), van Jaarsveld and Scheller-Wolf (2015) and Nadar, Akan, and Scheller-Wolf (2016) tackle this challenge. Horng and Yang (2012) propose an ordinal optimization-based evolution algorithm for an assemble-to-order system with truncated normal production lead times, a base-stock component replenishment policy and lost sales. The objective of their algorithm is to determine a profit maximizing target inventory levels within a limited computation time. The authors formulate the problem as a combinatorial optimization problem and propose a genetic algorithm to selecting multiple excellent solutions. They present the solution quality and computational efficiency of the proposed algorithm for an assemble-to-order system with 10 components and 6 end products. Huang et al. (2014) combine the global search ability of genetic algorithms and local search ability of simulated annealing algorithms into a hybrid genetic simulated annealing algorithm. They apply this algorithm to an assemble-to-order system with setup costs and simultaneous just-in-time and (r, Q) replenishment policies. They compare the accuracy and reliability of the hybrid and genetic algorithms by solving for the mixed replenishment policy of an assemble-to-order system with 20 components and 2 end products and suggest that the hybrid algorithm is dominant in finding global optimal solutions. van Jaarsveld and Scheller-Wolf (2015) develop a stochastic programming and sample average approximation algorithm to compute the near-optimal base-stock levels of an industrial-scale assemble-to-order system with backordering and FCFS allocation policy. They introduced a lower bound on the expected cost of the best base-stock policy. van Jaarsveld and Scheller-Wolf (2015) analyze the impact of the FCFS allocation policy on the performance of the system and they conclude that this allocation policy acts well for large assemble-to-order systems. Nadar et al. (2016) study an assemble-to-order system with general product structures. They adapt the lattice-dependent base-stock and lattice-dependent rationing policies introduced by Nadar et al. (2014) to these systems. The authors compare the performance of these policies with state-dependent base-stock and rationing policies and fixed base-stock and rationing policies. They conclude that the lattice-dependent policies outperform the state-dependent and fixed ones with respect to both objective value and computation time.

As it is evident from the studies summarized in this section, approximate methods make assumptions on component replenish-

ment and allocation policies and try to determine optimal or approximate system parameters. Since exact analysis are only possible for specific systems under specific assumptions, we expect more approximation methods analyzing assemble-to-order systems of realistic scale to emerge. Applicability of these approximations depend on performance guarantees.

Table 4 summarizes the literature on continuous-review, multiple end products assemble-to-order systems. For all studies discussed in Section 3.2 we provide details on replenishment and allocation policies, backordering or lost sales assumption and component lead times. The studies are on two-echelon assemble-to-order systems with negligible assembly lead time. The abbreviations SD, LD, Exp. and D stand for state-dependent, lattice-dependent, exponential and deterministic, respectively.

4. Conclusions

In this paper, we have reviewed scholarly works that deal with various problems related to assemble-to-order systems. This literature has been growing quickly in the past few years and we have attempted to provide a comprehensive review to serve as a reference for researchers who work in the field.

Based on our review, we conclude that the study of single end-product systems is more or less complete. Additional complexities could be added, but for practical purposes it suffices to know what replenishment policies should be used. State-dependent base-stock policies emerge for most systems studied. It depends on the particular demand and supply process to what extent optimal policies can be applied.

The single period and single order models have been studied under the heading of assemble-to-order systems. However, assemble-to-order systems are generally considered in practice for end products that are unique by combining a finite amount of modules and components. The demand for these modules and components is recurring, so that it is economically viable to hold inventory for them. One should be aware that the position of the customer order decoupling point (Hoekstra & Romme, 1992) is primarily driven by demand volatility for end products and their child items. Assemble-to-order systems apply when final assembly takes less time than the customer lead time that is required in the market. The single period and single order models apply to the so-called engineer-to-order systems. Examples of such systems are building and infrastructure construction, prototype high-tech systems, and defense systems. Another notion used for such systems is one-of-a-kind systems. It is important to base the modeling categorization in the field of multi-item multi-echelon systems on the widely applied concept of the customer order decoupling point. Thus we distinguish between make-to-stock, assemble-to-order, make-to-order (where only components are held in inventory) and engineer-to-order (where no inventory is held of components, but timing component ordering is the name of the game). More recently, new notions like configuration-to-order and build-to-order emerged in practice. We consider these notions special cases of assemble-to-order systems.

The systems with multiple end products cannot be solved to optimality in general. However, considerable progress on identification of optimal policies for specific assemble-to-order systems has been made. The study of N -, M -, and W -systems under various assumptions on cost parameters and lead times have provided further insight on the characteristics of optimal inventory replenishment policies and optimal component allocation policies. The application of stochastic programming has not only led to solution procedures for large-scale systems, but also to the development of new policies that are optimal for special assemble-to-order systems and asymptotically optimal for a wider class of systems (Dogru et al., 2017).

The study of assemble-to-order systems has shown that two aspects of multi-item multi-echelon systems need to be addressed: allocation of components to end products, and synchronization of replenishment orders of different components in the same end products. The way allocation and synchronization must be implemented depends strongly on the lead time distribution. For systems with exponential lead times, for which we know the optimal policy, allocation is dealt with by critical level policies and synchronization is dealt with by state-dependent base stock policies. The latter mechanism seems to extend to systems with constant lead times, while the former does not. This is due to the complexity of optimal allocation policies in divergent systems with constant lead times.

Assemble-to-order systems assume that customers are willing to wait longer than the time needed to assemble the end product from modules and components. Thus the trade-off between cost of customer waiting time must be traded-off against cost of investments in resource flexibility and inventories. Various authors have provided insight into the relevant trade-offs, in particular the impact of demand volatility. It seems that the trade-off needs to be considered for each specific situation, as some outcomes are qualitatively complex even for relatively simple situations.

New features have been added to assemble-to-order systems, such as pricing and disruptions. However, the added complexity of the system yields added complexity of optimal policies and managerial insights are problem- and instance-specific.

Numerical studies on complex assemble-to-order systems show that the component allocation policy and the component replenishment policy are of equal importance for realistic problem instances. We should be aware that in the business-to-business context service levels of 80% are quite common and this is the range where this equal importance applies. This equal importance seems to relate to the non-negligibility of remnant stocks under service levels below 90%. This implies that analysis of assemble-to-order systems ignoring remnant stocks is likely to fail in capturing the main trade-offs.

It follows from many studies that FCFS allocation of components to end products is non-optimal from a cost-perspective. Having said this, we should be aware that penalty costs are typically end product dependent, but not customer-dependent. From a customer perspective FCFS might better manage the customer waiting time than cost-optimal policies. Admittedly, this is a speculative statement, but we emphasize here that this aspect needs to be studied in order to make a relevant contribution to practice.

Given the complexity of optimal policies for assemble-to-order systems in special cases, the recent research on the structure of “myopic-optimal” policies is quite relevant. As these policies seem to perform well in special cases, it makes them a candidate for further exploratory research.

5. Future research directions

The literature on assemble-to-order systems is likely to continue to grow over the coming years. In this section, we identify multiple promising future research directions.

Probably the most important next step to take in the analysis of assemble-to-order systems is to propose policies for multi-echelon systems. So far, the far majority assumes that there is only a single echelon at which inventory is held. Real-world assemble-to-order systems consist of multiple echelons upstream of the original equipment manufacturer assembling the end product that hold inventory (and invest in resources). Only a few papers propose policies that are applicable to multi-item multi-echelon assemble-to-order systems. Clearly, base-stock policies can be used in multi-item multi-echelon systems, yet component allocation policies may be different at higher echelons, as they replenish inventory and

do not satisfy customer demand. Also synchronization mechanisms regarding component replenishment are likely to get more complex.

Rolling scheduling procedures based on periodically updating deterministic models are commonly (possibly exclusively) used in practice. In [de Kok and Fransoo \(2003\)](#) it is shown that this procedure yields suboptimal results. Recent research has provided numerical methods to solve more realistically sized assemble-to-order systems with some performance guarantee within a class of policies, in particular base-stock policies for component inventory replenishment. There is a need for further exploratory research based on a common test-bed of assemble-to-order systems. As stated earlier, there is no hope to find optimal policies for realistic assemble-to-order systems. Developing generally applicable policies that can be compared against other policies is the next best the operations research and operations management community can provide. This is comparable to the current practice in the field of combinatorial optimization. This allows both further development of deep theoretical insights, e.g. concerning asymptotic optimality in some sense, or optimal policies for special structures, and engineering research on solution procedures for problems of realistic sizes.

A promising avenue for further research is the identification of specific properties of optimal policies within a class of policies, which allow fast computation of optimal policies within this class. This line of research has been exploited in [Diks and de Kok \(1998\)](#), [de Kok and Fransoo \(2003\)](#), [de Kok \(2003\)](#), and more recently in [Atan, de Kok, Dellaert, van Boxel, and Janssen \(2015\)](#), to efficiently solve large-scale problems. In all cases recursive Newsvendor equations emerged as optimality equations to be solved to determine policy parameters. Clearly, this line of research contributes to the former one.

As assemble-to-order systems are typical for low-volume high-tech systems, the life cycle of product families is characterized by continual engineering changes. These can be seen as disruptions. As lead times of key components and modules are quite long, an untimely engineering change can be quite costly as it may make pipeline stocks obsolete at the original equipment manufacturer or its suppliers. The problem of engineering changes has been high on the agenda of most companies operating an assemble-to-order supply chain, yet it has received little attention in operations research and operations management literature. Clearly, rigorous research can make considerable contributions to practice.

In most papers the focus is on inventory management, given the lead times and bill-of-material (BOM) structure. A few papers recognize that lead times are a result of investment into resources and likewise the BOM structure. As assemble-to-order systems emerge in highly volatile supply and demand environments, more research is needed to identify the trade-offs between customer service, resource investments, material investments, and research and development investments, as well as the associated costs over time. Development of stylized models based on specific practical contexts capturing the main trade-offs, should provide both insights into appropriate managerial strategies, and building blocks for strategies that can cope with realistic problems.

It is out of the scope of this paper to formulate a complete research agenda for the study of assemble-to-order systems. We have argued that it is important to distinguish assemble-to-order systems from make-to-stock systems and engineer-to-order systems. With that distinction one may state that the focus on inventory management of assemble-to-order systems is justified, as final assembly adds relatively little value in that context. For make-to-stock systems we expect that a more balanced view on inventory and resource management is needed, while for engineer-to-order systems the focus should be on resource management. We advocate to make this distinction more clearly in

future research papers, thereby better aligning with the distinction made in industry for over 40 years.

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