

Chapter 8

Green Inventory Management

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8.1 Introduction

Managing inventories and thereby controlling the material flows through a facility, or network of facilities, is a matter of key importance in achieving efficient supply chains. Core issues in traditional inventory management are *how much to order when and where to satisfy the customers' service needs at minimum cost?* In this context, reasons for keeping inventory are economies of scale in batch ordering/production, and/or uncertainties in demand and supply. However, inventory management may also involve strategic decisions regarding design of distribution and production networks, facility location, procurement, supplier selection, choice of product range, etc. Many of these strategic issues are treated thoroughly in other chapters of this book, and will not be further discussed in this chapter. Instead, we will focus on the core operational issues and define inventory management in line with the operations research and management science (OR/MS) literature on inventory control and inventory modeling. It should be noted that closed loop systems encompassing reverse logistics flows, which is part of this literature, are treated separately in Chap. 17 by Abbey and Guide (2017).

In green (or sustainable) inventory management, the pure economic focus (traditionally measured in terms of costs) is complemented with an environmental perspective (typically measured in terms of emissions). This means that potential trade-offs need to be identified and resolved. Thus, green inventory management in the context of this chapter is concerned with the overarching question of how to

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efficiently manage inventories (and thereby material flows) with respect to both costs and emissions. An important insight is that inventory decisions are interlinked with production and transportation decisions that directly influence emissions. A total cost and emissions perspective is therefore important in green inventory management to avoid suboptimization and achieve cost-efficient emission reductions. Crudely speaking, emissions are often divided into three categories: Green House Gases (GHG), other harmful gases, and particles. Among these, GHG emissions (for convenience often measured in CO₂ equivalents) are getting most of the attention in media, and society at large, because of its impact on global warming. This is also reflected in the OR/MS literature on green inventory management and in the contents of this chapter. (Chap. 3 by Boukherroub et al. (2017) focuses entirely on carbon footprinting.) However, it is important not to forget that environmental consequences are not limited to (GHG) emissions and may, for example, include: noise, accidents, waste product accumulation in landfills and oceans, chemicals that pollute our air, ground, and water supply, deforestation and exploitation of natural resources that damage our ecological systems, etc. (Chap. 2 by Guinée and Heijungs (2017) introduces LCA and, in doing so, a full spectrum of environmental impact categories.)

Looking at how inventory management decisions may influence emissions, we first note that emissions are associated with energy consumption. Thus, decisions that affect the energy consumption of the supply chain will influence its emissions. With this in mind one may divide the emissions associated with operating an inventory system into three categories: *emissions associated with ordering (i.e., producing and transporting) items*, *emissions associated with holding items in stock*, and *emissions associated with not satisfying customer demand on time*. Note that this partition mirrors the cost components usually considered in inventory management: *costs for ordering/procuring items*, *costs for holding items in stock*, and *shortage costs for not satisfying customer demands on time*.

In the remainder of this introduction, we will take a closer look at these three categories of emissions and costs and use them as a basis for identifying key questions and challenges for green inventory management research. Basic inventory modeling structures, assumptions, and issues are also discussed. This is followed by an overview of the existing green inventory management literature in Sects. 8.2 and 8.3, which illustrate what issues and challenges have been addressed in the literature so far, and how. Section 8.2 considers deterministic demand models and Sect. 8.3 stochastic demand models. We also distinguish between single-echelon and multi-echelon inventory systems. Section 8.4 concludes with remarks about findings, practical implications, and what remains to be done in.

8.1.1 Emissions and Costs Associated with Ordering Items

The decision of when and how much to order is intricately connected to the issue of how ordered items should be produced and/or transported. For example, larger lot (or order) sizes in manufacturing, especially in energy-intensive process industries,

may have a significant impact on the energy use and emissions. However, it also leads to more finished goods and work in process inventory. The importance of transportation from an emissions point of view is apparent. For example, by choosing a greener transport mode such as sea or rail instead of road or air, the transport emissions, and generally also the transportation costs, can be reduced. Similarly, by employing shipment consolidation strategies and shipping full truck-loads and containers less frequently, the transportation capacity is better utilized. This means fewer vehicles are needed to ship the same volume suggesting less transportation emissions, and typically lower transportation costs for operating the system. The problem is that these strategies, which appear attractive when transportation is considered in isolation, can have negative consequences for the system as a whole. For example, greener transportation modes are generally slower, and often associated with larger fixed costs, suggesting longer transportation lead times and larger order sizes/shipment quantities. This means more inventory, and thereby increasing costs and emissions for holding inventory. Similarly, shipment consolidation suggests larger, less frequent, and/or less flexible shipments, and thereby more inventories. It is also noteworthy that these strategies are at odds with general perceptions of Just In Time (JIT) and LEAN, where frequent shipments of small batches are often implied.

8.1.2 Emissions and Costs Associated with Holding Items in Stock

The fact that there are costs of holding items in stock is undisputed. How these costs should be determined in practice is often more of an issue. The norm is to assume that they are proportional to the number of items in stock. (As some of the cost components usually are fixed, or tend to increase stepwise with the number of units in stock, the appropriateness of assuming linear holding costs may sometimes be questioned). The holding cost per unit and time unit can be divided into two main components: cost of capital, and out-of-pocket holding costs. The former is generally determined as a holding cost rate multiplied by the monetary value of the item. It should reflect the opportunity cost of tying up capital in inventory instead of in other investment opportunities. Conversely, the out-of-pocket holding cost rate should reflect the costs of operating the inventory facilities (including energy costs), handling the items, and losing items because they perish, are stolen, destroyed in accidents, misplaced, etc. The emissions associated with holding items in stock are clearly connected to the energy consumption of operating the inventory facilities and handling the items, but also to items that are discarded and wasted. An important example of the latter is food (often with high CO₂ content) that perishes and is thrown away. For instance, the Swedish Institute for Food and Biotechnology (SIK) 2011, reports that roughly one-third of the food produced for human consumption is lost or wasted globally. Furthermore, in high income countries, one of the main reasons for the waste is lack of coordination between demand and supply. For more in-depth discussions of challenges and issues in sustainable food supply chain

design, we refer to Chap. 18 by Bloemhof and Soysal (2017). Another less obvious emission source can be leakage of pollutants. As an example, Walmart states that leakage of highly potent GHG refrigerants account for 13% of their total GHG footprint, which is almost twice as much as what the fuel to their trucks account for (Walmart Global Responsibility Report 2013). This emphasizes the fact that the emissions of operating inventory facilities and stock handling is case dependent, and very much affected by the type of products considered. If a temperature-controlled environment is needed, as is the case for frozen or refrigerated products, the energy consumption and thereby emissions of holding items in stock are much higher and more important to consider than if items are stored in a non-heated warehouse or outdoors. Another example, in contrast to refrigerated products, is that many chemical companies, such as Eastman, at least for limited periods, store products in molten form, which requires a lot of energy.

Generally speaking, more inventories suggest increased costs and emissions, although exactly how and to what extent is often more difficult to say without a careful analysis. Assuming a proportional relationship, which is often done, is convenient, but may not always be appropriate. Relating inventory holding costs and emissions to the strategies for reducing production and/or transport emissions and costs above (e.g., use of greener transport modes, and shipment consolidation) illustrates important trade-offs. Reducing transport emissions and costs may lead to more inventory suggesting increased emissions and costs for holding items in stock. Resolving trade-offs like this to minimize *total costs and emissions* for the system is a key challenge in green (or sustainable) inventory management.

8.1.3 Emissions and Costs Associated with Not Satisfying Customer Demand on Time

The purpose of the inventory system is to provide adequate service to its customers. Not satisfying customer demands on time have negative impact on the customers as they are not receiving the service they expect. This negative impact can be translated into shortage costs for the inventory system. The shortage cost may be a fixed cost per shortage or it may be dependent on the time a customer has to wait for an item (it is then often referred to as a backorder cost). The shortage cost can reflect concrete monetary reimbursements or price discounts in case of delayed deliveries. It should also reflect loss of goodwill in terms of foregone future sales and revenues. Some shortage cost components may be relatively easy to determine, such as downtime costs in a machine or in a production facility. Other shortage cost components, such as loss of goodwill and future revenues, are more difficult to ascertain. These difficulties explain why service (level) constraints are more popular in practice than shortage costs. On the other hand, shortage costs are the preferred choice in the research literature as measuring all performance aspects in monetary terms enables a total cost perspective. Thus making it less ambiguous to compare the performance of different policies where the exact same service cannot be achieved.

The negative consequences of not satisfying customer demands on time may also involve increased emissions. For example, consider a dairy where a machine breakdown halts the production process. If the necessary spare part is not available within hours, the semi-finished milk products in the process must be discarded, and the facility needs to be cleaned before it can be restarted. Clearly, the emissions associated with throwing away a production batch of dairy products, and steam-cleaning the process facility are significant. Another example of emissions associated with not satisfying customer demand on time is the transport emissions of a customer making an extra trip, e.g., to IKEA, because the product was stocked out when she initially went there to buy it. In situations like this when poor service generates emissions at a firm's customer (Scope 3 emissions) there is a problem of how to allocate the emissions between the two parties. The problem is especially difficult if the customer, as in the IKEA example, has a choice to make the extra trip or not. Emission allocation issues are briefly discussed in Chap. 3 (Boukherroub et al. 2017). A common situation not complicated by emission allocation issues between the firm and its customers is when the firm uses emergency shipments to deal with inventory shortages. The extra transportation emissions for these emergency shipments may be interpreted as emissions for not satisfying customer demand on time through the regular inventory system. The emergency shipments are often associated with higher emissions than regular deliveries due to lower load efficiency in vehicles and use of faster, more energy intensive, transportation modes.

Similarly to shortage costs, the emissions associated with not satisfying customer demand on time can be more or less difficult to determine: In the dairy example above and in terms of emergency shipments, it is relatively straightforward although not without practical challenges. However, in the IKEA example it is more difficult as the second trip to IKEA in some cases would have been made anyway because the customer was going there to buy other products. Also, the length of the trip, and thereby the emissions, are different across customers, making it difficult to estimate. Although the emissions and costs associated with not satisfying customer demand on time are sometimes challenging to determine, they can be very important to consider in green inventory management. Returning to the dairy example above, which stems from a real case, the spare parts provider initially had the ambition to eliminate air freight, and switch to road and sea freight to reduce transport emissions. However, after further analysis, they concluded that these reductions were minute in comparison to the increased risk of not delivering spare parts fast enough to avoid production losses.

From the discussion above we can conclude that key challenges in green inventory management are to understand how a decision impacts the costs and emissions for the inventory system, and how to leverage this understanding to make the "best" decisions. The overarching goal is to minimize both costs and emissions, but decisions that minimize the system's costs rarely minimize its emissions and vice versa. Thus a key question is how these potentially conflicting objectives may be reconciled, or in other words, to define what "best" decisions means in different contexts. The main approaches used are to: (1) translate

emissions into environmental costs and minimize the total costs, (2) minimize the costs while restricting the total emissions to not exceed a given maximum value or cap, (3) minimize the costs under an emissions cap that can be traded on a market, and (4) use Multiple Criteria Decision Making (MCDM) techniques to combine the emission and cost perspectives. The latter may involve identifying efficient frontiers, Pareto optimal solutions, construction of utility functions etc. The former three reflects a hierarchical view where the main goal is cost minimization. From a company perspective, emission restrictions and environmental costs can reflect regulations and taxes imposed by society, or it may be based on voluntary commitments. Another form of the latter is investing in different types of carbon offsets (e.g., planting of trees).

An aspect worth noting is that depending on how the supply chain is organized, the types of emissions discussed above may (according to the GHG protocol) belong to Scope 1 (direct emissions, e.g., from company owned vehicles), Scope 2 (indirect emissions from electricity, heating, cooling, etc. purchased by the company) or Scope 3 (other indirect emissions, e.g., from customers and outsourced services, including transportation and warehousing). As outsourcing is very common in logistics (for example, companies today rarely have their own private transportation fleet), the Scope 3 emissions are significant. The challenges of measuring and allocating (Scope 3) emissions in supply chains are thoroughly discussed in Chap. 3 (Boukherroub et al. 2017) and will not be further discussed in this chapter.

Considering the relative size of the emissions discussed above, emissions for producing and transporting items are in general much larger than those for holding items in stock. For instance, the World Economic Forum (2009) estimates that about 90% of the emissions (measured in CO₂ equivalents) for logistics and transport activities are due to freight transportation, and 10% for operating logistics buildings. (Emissions associated with production, or not satisfying the customer on time, are not discussed in this report, which focuses on emission sources in logistics and transportation from a macroperspective). Moreover, the energy demand for freight transport is expected to continue to increase because of the globalization of trade and supply chains. The European Commission (2009) estimates a 60% increase in this energy demand from 1990 to 2030 (1990–2009 the observed increase was 36%). Thus from a climate perspective, reducing transport emissions is important. An obvious step in this direction is development of cleaner vehicle technologies, but the World Economic Forum (2009) also emphasizes several other important strategies including: despeeding the supply chain, optimizing transport networks, and switching of transport modes to greener alternatives. Important enablers for despeeding the supply chain, without significant cost increases due to prolonged lead times, are improved collaboration and information sharing between suppliers, customers, and other parties in the supply chain. With respect to optimized networks, the World Economic Forum estimate that 24% of the goods vehicle kilometers in the EU are associated with empty vehicles, and when carrying a load, vehicles are on average filled to 57% of their maximum gross weight. Altogether this indicates a large potential for increasing the capacity utilization of vehicles, for

example, through better shipment consolidation and multimodal transport solutions. From an inventory management perspective, all these strategies for greener transports (except perhaps cleaner vehicle technologies) suggests longer lead times, and thereby a need for more inventory, or a decline in customer service. Thus an important question in green inventory management is how to enable reduction in transport emissions without compromising customer service or increasing total costs and emissions. Here, green (or sustainable) management of multi-echelon (or multi-stage) inventory systems, with inventories upstream and downstream in the supply chain that jointly can compensate for lead time changes, offers interesting opportunities.

From a modeling perspective, the added complexity in green inventory management, compared to traditional cost-based inventory models, is to quantify also the emissions (or environmental consequences), and to find optimal decisions with respect to both costs and emissions. An important first step is then to be able to evaluate the expected emissions and costs associated with a decision. We note that in cases where the emissions accumulate in the same way as the costs, the expected costs and the expected emissions may be evaluated using the same method. Thus, if a traditional inventory management model already exists for evaluating the expected costs, the same model can be used also for determining the expected emissions. The remaining challenge is then to find the best joint decisions with regard to costs and emissions. Of course, if the emission and cost components cannot be modelled analogously, new evaluation methods are needed. Thus, an important question for green (or sustainable) inventory management modeling is to what extent it may be built on existing results. The fact that it requires careful balancing of costs against emissions emphasizes a need for precise models and evaluation methods in both dimensions. This means that traditional approximations and model assumptions, not least regarding costs, should be carefully analyzed before they are used.

8.2 Green Inventory Management Under Deterministic Demand

This section provides an overview of green inventory models that are based on the assumption that future demand is known with certainty. Such an assumption of deterministic demand can be appropriate in some situations, but clearly most often, future demand is uncertain. Still, deterministic models are often used with good results as heuristics for determining order quantities (or lot sizes) also when the demand is stochastic. Disregarding demand uncertainties simplifies the analysis. It is therefore a natural starting point for gaining some first insights of the cost and emission trade-offs that exist in green inventory management. An important aspect of this is the impact of different mechanisms for reducing emissions used by policy makers. Most of the literature on sustainable inventory control with deterministic demand is based on the well-known economic order quantity (EOQ) model for lot

sizing published already in 1913 by Ford W. Harris, (Harris 1913). We first present some of these results and then discuss some more elaborate models that extend and confirm the main insights gained from the simpler EOQ-models.

8.2.1 *The Single-Echelon EOQ-Model with Environmental Considerations*

The traditional EOQ-model considers a single inventory location and a single product with a constant and continuous demand D per time unit. The lead-time is zero and no backorders or lost sales are allowed so each time the inventory level goes to zero a new order is placed. Stock keeping in this simple setting is motivated by economies of scale in batch ordering/production as reflected by the fixed cost per order. The aim is to minimize the average cost per time unit of ordering and keeping this product in stock. Extensions to discrete demand, a positive lead-time, planned backorders, and a volume-based price per unit are straightforward (see, for example, Axsäter 2006), but will not be further discussed in this chapter.

Each time an order is placed in the EOQ-model, the firm incurs a fixed cost A per order and a variable cost c per unit purchased. The cost for an order of Q units is thus $A + cQ$ and such an order will be placed every Q/D time unit. There is a holding cost h per unit and time unit for inventory kept in stock. The average amount of inventory if one orders Q will be $Q/2$. The total cost per time unit, $Z(Q)$, can be divided into two parts; the per unit purchase cost, cD , and the inventory-related cost, $Z'(Q)$,

$$Z(Q) = \frac{AD}{Q} + h\frac{Q}{2} + cD = Z'(Q) + cD.$$

The cost-minimizing solution, which does not involve any environmental considerations, is of the well-known square root form

$$\min_Q Z(Q) \Rightarrow Q_z^* = \sqrt{\frac{2AD}{h}} \Rightarrow Z'(Q_z^*) = \sqrt{2AhD}.$$

Emissions are incorporated into the model using an emissions structure that mirrors the cost structure. To do so we introduce the emission parameters \hat{A} , \hat{c} and \hat{h} denoting the emission per placed order, per unit ordered, and per unit kept in stock for one unit of time. The average emissions per time unit, $E(Q)$, can then be expressed as

$$E(Q) = \frac{\hat{A}D}{Q} + \hat{h}\frac{Q}{2} + \hat{c}D = E'(Q) + \hat{c}D.$$

The associated emission minimizing solution, $\min_Q E(Q)$, is analogously

$$Q_E^* = \sqrt{\frac{2\hat{A}D}{\hat{h}}} \Rightarrow E'(Q_E^*) = \sqrt{2\hat{A}\hat{h}D}.$$

It follows that a reduction in emissions by adjusting the order quantity from the cost-minimizing solution can only be attained if the relationship

$$\alpha = \frac{\hat{A}/\hat{h}}{A/h} \neq 1$$

Note that if $\alpha = 1$, the two solutions, Q_Z^* and Q_E^* , will coincide. In all other cases, i.e., $\alpha \neq 1$, a reduction in emissions implies a deviation from the cost-minimizing order quantity, Q_Z^* and thus an increase in cost. The best ordering decision from a joint emission and cost perspective is the one that gives the lowest cost for a given amount of emission or vice versa, i.e., a solution that belongs to the efficient cost-emission frontier as depicted in Fig. 8.1. The properties of this frontier for the classical EOQ-problem are analyzed and discussed in Bouchery et al. (2012). Key results, illustrated in Fig. 8.1, are that the efficient frontier is convex, and that substantial emission reductions can be attained with only a modest increase in cost when the cost is close to optimal. The opposite holds when the inventory-related cost is far from optimal, that is, a large increase in cost is needed to attain a small emission reduction.

The behavior can be explained by the well-established fact that for the classic EOQ-problem, the total cost is fairly insensitive to changes in the order quantity around its optimum Q_Z^* . Conversely, the total cost is highly sensitive to such changes

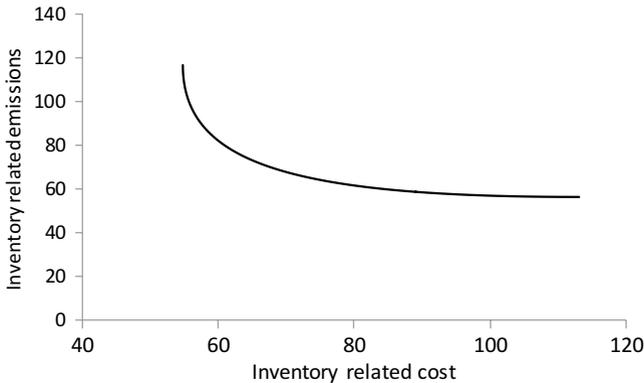


Fig. 8.1 Efficient cost-emission frontier for a single-echelon EOQ system (adapted from Bouchery et al. 2012)

when the order quantity is far from the optimum. This relationship between cost and emissions is formalized by Chen et al. (2013), which show that the relative reduction of the inventory-related emissions

$$\delta_E(\delta_Z, \alpha) = \frac{E'(Q_Z^*) - E'(Q(\delta_Z, \alpha))}{E'(Q_Z^*)}$$

as a function of the relative increase in inventory-related costs

$$\delta_Z = \frac{Z'(Q(\delta_Z, \alpha)) - Z'(Q_Z^*)}{Z'(Q_Z^*)}$$

is,

$$\delta_E(\delta_Z, \alpha) = \begin{cases} \frac{(\delta_Z - \sqrt{2\delta_Z + \delta_Z^2})(1 - \alpha + \delta_Z - \sqrt{2\delta_Z + \delta_Z^2})}{(1 + \alpha)(1 + \delta_Z - \sqrt{2\delta_Z + \delta_Z^2})}, & \text{if } \alpha < 1, \\ \frac{(\delta_Z + \sqrt{2\delta_Z + \delta_Z^2})(1 - \alpha + \delta_Z + \sqrt{2\delta_Z + \delta_Z^2})}{(1 + \alpha)(1 + \delta_Z + \sqrt{2\delta_Z + \delta_Z^2})}, & \text{if } \alpha > 1. \end{cases}$$

They also show that the maximum relative decrease in emissions compared to the cost-minimizing solution is $\delta_E = (E'(Q_Z^*) - E'(Q_E^*)) / E'(Q_Z^*) = (1 - \sqrt{\alpha})^2 / (1 + \alpha)$

which is attained with a relative increase in the cost of $\delta_Z = (Z'(Q_E^*) - Z'(Q_Z^*)) / Z'(Q_Z^*) = (1 - \sqrt{\alpha})^2 / 2\sqrt{\alpha}$

As mentioned earlier, Multiple Criteria Decision Making techniques based on efficient frontier analyses and/or formulas as the ones above is one of several approaches used for combining emission and cost considerations in green inventory management. The other approaches, i.e., to translate the emission into an environmental cost (for example, in terms of an imposed carbon tax), to use an emission constraint with a fixed cap, or to operate under cap and trade or cap and offset systems, have all been studied in the literature on green EOQ-problems, for example, in Chen et al. (2013) and Hua et al. (2011). These findings are summarized below.

If a tax of t is imposed for each emission unit, the average inventory-related cost per time unit is

$$Z_t(Q) = Z'(Q) + tE'(Q) = \frac{(A + t\hat{A})D}{Q} + (h + t\hat{h})\frac{Q}{2},$$

and the associated optimal (cost-minimizing) order quantity is

$$Q_t^*(t) = \sqrt{\frac{2(A+t\hat{A})D}{h+t\hat{h}}} \Rightarrow Z'_t(Q_t^*(t)) = \sqrt{2(A+t\hat{A})(h+t\hat{h})}D.$$

The order quantity $Q_t^*(t)$ is equal to the traditional cost-minimizing order quantity, Q_Z^* , if $t = 0$ (i.e., the tax rate is zero). Moreover, it approaches the emission minimizing order quantity, Q_E^* , as $t \rightarrow \infty$ (from above when $\alpha < 1$, and from below when $\alpha > 1$). With $u = \hat{A}/A$, and $v = \hat{h}/h$, the relative shift in inventory-related costs and emissions as a function of the tax rate is

$$\frac{Z'_t(Q_Z^*) - Z'_t(Q_t^*(t))}{Z'_t(Q_Z^*)} = 1 - \frac{\sqrt{(1+ut)(1+vt)}}{1+(u+v)t/2}$$

$$\frac{E'(Q_Z^*) - E'(Q_t^*(t))}{E'(Q_Z^*)} = 1 - \left(\frac{u}{u+v} \sqrt{\frac{1+vt}{1+ut}} + \frac{v}{u+v} \sqrt{\frac{1+ut}{1+vt}} \right)$$

Both of these relative changes are increasing in the tax rate with the limiting value $(1 - \sqrt{\alpha})^2 / (1 + \alpha)$ as the tax rate goes to infinity (see Chen et al. 2013 for details). The relative cost increase compared to a system without any tax can be substantial, and are equal to

$$\delta_{z,t} = \frac{Z'_t(Q_t^*(t)) - Z'(Q_Z^*)}{Z'(Q_Z^*)} = \sqrt{\frac{(A+t\hat{A})(h+t\hat{h})}{Ah}} - 1.$$

However, most of this increase in cost is due to tax payments. The increase of the sum of holding and ordering costs is still limited to $(1 - \sqrt{\alpha})^2 / 2\sqrt{\alpha}$ in accordance with the findings for the efficient frontier.

If a cap, C , is imposed on the average emissions per time unit we have

$$E'(Q) = \frac{\hat{A}D}{Q} + \hat{h} \frac{Q}{2} \leq C' = C - c'D.$$

This restricts the possible order quantities to

$$Q_L(C') \leq Q \leq Q_U(C')$$

where

$$Q_L(C') = \frac{C' - \sqrt{C'^2 - 2\hat{A}\hat{h}D}}{\hat{h}} \quad \text{and} \quad Q_U(C') = \frac{C' + \sqrt{C'^2 - 2\hat{A}\hat{h}D}}{\hat{h}}$$

As $Z(Q)$ is convex in Q , the optimal (cost-minimizing) order quantity under a carbon constraint is

$$Q_C^*(C_{,,}) = \begin{cases} Q_L(C_{,,}) & Q_Z^* < Q_L(C_{,,}) \\ Q_Z^* & Q_L(C_{,,}) \leq Q_Z^* \leq Q_U(C_{,,}) \\ Q_U(C_{,,}) & Q_Z^* > Q_U(C_{,,}) \end{cases}$$

The inventory policy and the inventory-related emissions, $E'(Q_C^*(C')) = \min(E'(Q_Z^*), C')$, is independent of the cap as long as the constraint is not violated by the traditional cost-minimizing policy, Q_Z^* .

If a cap and trade system is used for regulating emissions, it is possible to purchase emission rights to relax the constraint, or to sell unused emission rights if the firm's emissions are below the cap. If the buying and selling price of the emission rights, p , are the same, and potential revenue from trading is viewed as a negative cost, the average inventory-related cost under cap and trade is

$$Z'(Q) = Z'(Q) + p(E'(Q) - C') = \frac{(A + p\hat{A})D}{Q} + (h + p\hat{h})\frac{Q}{2} - pC'.$$

Comparing this cost expression with the one where an emission tax is applied, $Z'(Q)$, we can see that they are indeed very similar. The difference is that the price for emissions, p , has replaced the tax rate, t , and that an adjustment, pC' , is made as one only pays for the emissions in excess of the cap. Consequently, the optimal solution is also similar

$$Q_{C\&T}^*(p) = \sqrt{\frac{2(A + p\hat{A})D}{h + p\hat{h}}} \Rightarrow Z'_{C\&T}(Q_{C\&T}^*(p)) = \sqrt{2(A + p\hat{A})(h + p\hat{h})D} - pC'.$$

In fact, the EOQ-model with an emission tax, can be viewed as a special case of the same model with a cap and trade mechanism, with the cap set to zero, and price of emission rights, p , set to the tax rate t . A major difference between a cap and trade system and tax system (also when $p = t$) is that the former implies less of a cost increase for the firms (except when $C' = 0$) as one gets a reimbursement equal to pC' . For some firms the revenue from selling emission rights might even exceed their increase in inventory-related cost. This means they are better off under a cap and trade system than without any regulations.

Interestingly, from the expression for $Q_{C\&T}^*(p)$ we can see that there is no direct connection between the cap, C , and the optimal inventory policy. There should be an indirect connection though, as reduced caps imply an increased demand for emission rights. This should increase the price p and push $Q_{C\&T}^*(p)$ towards the emission minimizing order quantity, Q_E^* . Some companies will benefit from a general reduction of the cap whereas others will lose money.

A cap and offset system is similar to a cap and trade system but it does not allow companies to sell emission rights. The optimal (cost-minimizing) policy in such a system is given by

$$Q_{C\&O}^*(p, C') = \begin{cases} Q_{C\&T}^*(p) & \text{if } Q_Z^* \leq Q_{C\&T}^*(p) \leq Q_L(C') \\ Q_L(C') & \text{if } Q_Z^* \leq Q_L(C') \leq Q_{C\&T}^*(p) \\ Q_Z^* & \text{if } Q_L(C') \leq Q_Z^* \leq Q_U(C') \\ Q_U(C') & \text{if } Q_{C\&T}^*(p) \leq Q_U(C') \leq Q_Z^* \\ Q_{C\&T}^*(p) & \text{if } Q_U(C') \leq Q_{C\&T}^*(p) \leq Q_Z^* \end{cases}$$

This means that the cost-minimizing order quantity, Q_Z^* is chosen if possible. Otherwise, the optimal order quantity is determined by the cap, via $Q_L(C')$ and $Q_U(C')$, or by the optimal cap and trade solution, $Q_{C\&T}^*(p)$. Note that $Q_{C\&T}^*(p)$ implies that emission rights are sold if $Q_L(C') < Q_{C\&T}^*(p) < Q_U(C')$. Hence, $Q_{C\&T}^*(p)$ is not a viable solution in a cap and offset system in this interval. The cap and offset system can be viewed as a special case of a cap and trade system with buying price of emission rights, p , and selling price of zero. Any cap and trade system with a difference in buying and selling price of emission rights will exhibit similar structure. Albeit with seven possible order quantities as emission rights will be sold if the optimal order quantity when doing so falls between $Q_L(C')$ and $Q_{C\&T}^*(p)$, or $Q_U(C')$ and $Q_{C\&T}^*(p)$.

8.2.2 Extensions of the Single-Echelon EOQ-Model with Environmental Considerations

Extensions of the single-echelon EOQ-model with environmental considerations found in the literature include alternative cost/emission structures, non-stationary demand, and multi-echelon models.

Several authors, Battini et al. (2014), Bozorgi et al. (2014), and Konur and Schaefer (2014) consider non-linear (stepwise increasing) ordering costs and emissions to capture the limited capacity of trucks and similar transportation resources. Problems with non-linear ordering cost are not new but one can argue that they are of particular interest for environmental considerations as much of the transport emissions are due to the movement of the actual vehicle. Konur (2014) elaborates further on this problem by integrating the design of the transportation fleet into the inventory management decisions.

Toptal et al. (2014) consider the EOQ-model where there exists an alternative emission-reducing investment. In a cap and trade system, the optimal order quantity is still $Q_{C\&T}^*(p)$. The reason is that an emission reduction leads to the same saving or revenue no matter how it is achieved. In contrast, in a system with a fixed cap, the optimal ordering quantity and the alternative emission-reducing investment will be interdependent. To achieve an emission reduction, an

adjustment of the order quantity will always be made. The alternative emission-reducing investment is used as a complement if the reduction required to reach the cap is substantial.

Inventory problems with deterministic non-stationary demand are considered in Benjaafar et al. (2013), Absi et al. (2013) and Helmrich et al. (2015) among others. Benjaafar et al. (2013) make a number of observations based on a series of numerical experiments that are in line with what can be deduced directly from the EOQ-model discussed above. In addition they point to the fact that if the emission cap is not based on the long-run average but is imposed on a given period, then a tighter cap might lead to higher total emissions (something that applies to the problem with stationary demand as well).

The literature on green inventory control in a multi-echelon setting with deterministic demand is more limited. Bouchery et al. (2012) extend the analysis of the efficient cost-emission frontier to a two stage serial system. For a single criteria problem, the optimal policy is a stationary nested policy, i.e., the higher echelon always order an integer multiple k of the lower echelon's order quantity. For a multi-criteria problem, the optimal policy is still nested but not necessarily stationary. This is illustrated in Fig. 8.2 that shows the frontier for the best combined policy as well as the efficient frontier of a number of stationary-nested policies.

The analysis in Bouchery et al. (2012) focuses on stationary policies arguing that such policies are easier to implement in practice. In the non-convex segments of the frontier of stationary policies, a better solution can be obtained using a linear combination of two nested policies, represented by the dotted straight line in Fig. 8.2. This renders the true cost/emission frontier. Thus, in contrast to a single-echelon system, the optimal policy in a serial system is not necessarily stationary even under constant demand.

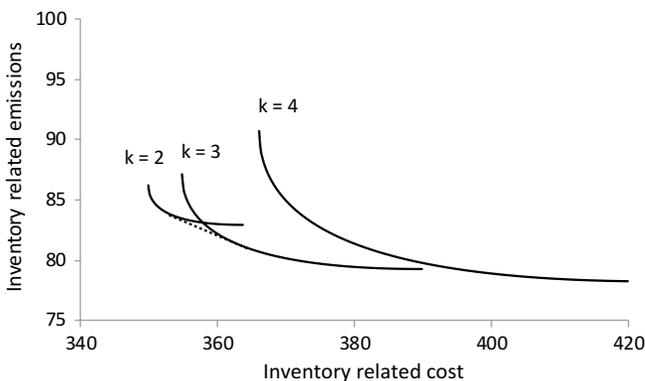


Fig. 8.2 Efficient cost-emission frontier in a serial system (adapted from Bouchery et al. 2012). The solid line depicts the efficient frontier for stationary nested policies with $k=2, 3$, and 4 respectively. The efficient frontier for all policies is a combination of these and the dotted line which is a non-stationary policy

Benjaafar et al. (2013) investigates the cost benefit of collaborating in a supply chain in order to meet emission caps. They show numerically that the relative benefits can be substantial, particularly for mid-range emission caps. When the cap is high, it has little influence on the supply chain. If the cap is low, the cost for the supply chain to adhere to it will be very high, and the relative savings of collaborating to meet the cap will be low, even if they might be high in absolute values. They also show that as always, it is important that the benefits of collaboration are not distributed in a too unfair manner. If they are, some parties might prefer to not collaborate as this will increase their costs, even if the total cost for the supply chain decreases. Wahab et al. (2011) investigate supply-chain collaboration in an EOQ-setting considering imperfect items and environmental impact. The latter is captured as a tax on emissions, and they assume that there are no emissions linked to holding inventory. Their numerical examples show a reduction of the order-quantity when environmental considerations are taken. With a larger amount of emissions linked to holding inventory, the results could, of course, be reversed.

8.3 Green Inventory Management Under Stochastic Demand

In this section we extend the scope to green inventory management models that deals with demand uncertainty. In these models, the demand is represented by stochastic (or random) variables with known probability distributions. A stochastic variable can have many different outcomes, and the probability (or density, if it is a continuous variable) for each outcome is specified in a probability distribution. In practice, demand is almost always uncertain, and arguably one of the main reasons for stock keeping in practice is to buffer against this uncertainty, and maintain acceptable customer service. The importance of stochastic demand models in inventory management is therefore undisputed. In the following, we will consider a range of green inventory models available in the literature to illustrate and explain how the different challenges and trade-offs discussed in the beginning of this chapter are considered. We first focus on single-echelon models and then extend the scope to multi-echelon models involving networks of inventory locations. (We assume the locations as given; in Chap. 9, Velásquez Martínez and Fransoo examine green facility location.) For reasons of space, some models are treated more briefly than others. This does not mean that they are less important or interesting. Mathematical details of more complex models are omitted.

8.3.1 *Single-Echelon Models for Green Inventory Management*

A single-echelon inventory model considers a single stock-point in isolation. One of the simplest and most widely used single-echelon inventory models for stochastic demand is the newsvendor model. It considers a single product in a single period (or selling

season) and may be appropriate for seasonal goods, fashion clothing, and high tech products with very short lifecycles. Our exposur  begins by considering green inventory management in newsvendor settings. The scope is then extended to more general inventory management situations with multiple periods and replenishment opportunities.

8.3.1.1 Green Inventory Management in Newsvendor Settings

The classical newsvendor model assumes that the demand during the selling period is stochastic, and at the end of the period there are overage (holding) costs associated with every unsold unit, and underage (shortage) costs associated with every unsatisfied demand. The focus is on the inventory management decision of how many units to order for the coming period, when the objective is to minimize the expected overage (holding) and underage (shortage) costs. An alternative objective is to maximize the expected profit for the considered period by also taking purchase and selling prices per unit into consideration.

To illustrate how the newsvendor framework can be used for green inventory management, we consider a dual sourcing model analyzed in Rosi  and Jammerneegg (2013), and Arkan and Jammerneegg (2014). Together these two papers consider costs and emissions associated with ordering, producing, and transporting items and with holding items in stock. They also consider different types of emission regulations and emission constraints for a profit maximizing firm. More precisely, Rosi  and Jammerneegg (2013) investigate the economic and environmental impact of dual sourcing for three scenarios of emission regulations: (1) no regulations, (2) an emission (or carbon) tax and (3) a cap and trade system with fixed price emission allowances. In their model a profit maximizing firm has the option to source from a low-cost offshore supplier before a given selling season starts, or to use a more expensive, fast, onshore supplier, when demand has been realized at the end of the selling season. Transporting goods from the offshore supplier is associated with transport emissions, while transport emissions from the onshore supplier are negligible. During the selling season there is a stochastic demand for X units, and the firm sells the product at unit price p . Unsold products (in inventory) at the end of the season has a per unit salvage value z , which includes the inventory holding costs. The firm procures q units from the offshore supplier at the unit price c before the season starts, and the rest from the onshore supplier at unit price $c + d$ at the end of the season when the demand is known. It is assumed that $p > c > z$, and $p > c + d$ so that the onshore supplier is an option to consider. Thus, if a demand of x units is realized $\max(x - q, 0) = (x - q)^+$ units are purchased from the onshore supplier. This corresponds to the underage or lost sales in the classical newsvendor model. Moreover, the underage cost is d , the overage cost is $c - z$, and the firm's profit function, given q and x , is

$$P(q, x) = \begin{cases} (p - c)x - (c - z)(q - x) & \text{if } x \leq q \\ (p - c)x - d(x - q) & \text{if } x > q \end{cases}$$

The expected profit, given the offshore order quantity q , is obtained by taking the expectation with respect to the demand X

$$P(q) = E[(p - c)X - (c - z)(q - X)^+ - d(X - q)^+].$$

Letting $F(x)$ denote the cumulative distribution function (cdf) of the continuous demand X , and $F^{-1}(\cdot)$ its inverse, it follows from the classical newsvendor analysis that the optimal offshore order quantity is

$$q^* = F^{-1}\left(\frac{d}{d + c - z}\right).$$

Introducing a transportation emission tax, t , per unit shipped from the offshore supplier increases its per-unit costs to $c + t$. This decreases the optimal amount procured offshore, q^t , and thereby the transport emissions, but it also decreases the expected profit.

$$P(q) = E[(p - c - t)X - (c + t - z)(q - X)^+ - (d - t)(X - q)^+].$$

$$q^t = F^{-1}\left(\frac{d - t}{d + c - z}\right)$$

As an alternative to the linear emission tax, the authors also consider an emissions trading system, where the company, free of charge, receives emission allowances corresponding to an emission cap of L products transported from the offshore supplier. The firm can buy more emission allowances at the per unit price b , and sell allowances it does not use at the per unit price s ($b \geq s$). This means that the transport emission costs are $b(q - L)^+$, the revenue of selling unused emission allowances is $s(L - q)^+$, and the expected profit for emission cap L and offshore order quantity q is:

$$P_L(q) = \begin{cases} P_s(q) & \text{for } q \leq L \\ P_b(q) & \text{for } q > L \end{cases}, \text{ where } \begin{cases} P_s(q) = P(q) + s(L - q) \\ P_b(q) = P(q) - b(q - L) \end{cases}.$$

It is straightforward to show that the optimal offshore order quantity for an emission cap of L , q^L , is obtained as a two-sided control limit policy

$$q^L = \begin{cases} q^b & \text{for } L < q^b \\ L & \text{for } q \leq L < q^s \\ q^s & \text{for } L > q^s \end{cases}$$

Here q^b and q^s maximizes $P_b(q)$ and $P_s(q)$, respectively, and are easily obtained as

$$q^b = F^{-1}\left(\frac{d - b}{d + c - z}\right) \text{ and } q^s = F^{-1}\left(\frac{d - s}{d + c - z}\right)$$

Note that $b \geq s$ implies that $q^b \leq q^s$, and that $s=b=0$ brings us back to the basic dual sourcing model without emission regulations. Moreover, $L=0$ and $b=t$ renders the emission tax model.

From the above expressions one can conclude that $q^L < q^*$, meaning that the offshore order quantity, and thereby the emissions are reduced through the emission trading system. One can also see that the smallest offshore order quantity under the emission trading system is q^b . Thus, setting the cap, L , lower than this will not reduce the transport emissions further it will only decrease the firm's profit.

In a numerical study based on normally distributed demand, the authors illustrate that dual sourcing as described in this stylized model can reduce emissions and improve economic performance in comparison to single sourcing from an offshore supplier. By implementing environmental regulations in terms of a linear transport emission tax or a cap and trade system, the transport emissions can be further reduced. Both an emission tax and a cap and trade system are in the context of this model very effective tools to reduce emissions, but the emission tax tend to affect the firm's profit more severely. Under the cap and trade system profits can even increase, as the firm may generate extra revenues by selling emission allowances it has received for free but do not need. These results indicate that from the firm's perspective a cap and trade system is preferred over an emission tax.

Arikan and Jammerneegg (2014) consider the same dual sourcing model, but when a Product Carbon Footprint (PCF) constraint, set voluntarily or by regulators, is used to limit the emissions. Hence, the management objective is to maximize the profit, $P(q)$, subject to the PCF constraint. The carbon footprint may be used for differentiating the firm's products, for example, by displaying it on an eco-label. The emissions considered in the model are production, transportation, and warehousing activities. Emissions caused customers by usage and consumption are excluded. The emissions related to holding items in stock (overage), including disposal of products or shipping them to secondary markets, etc. are modelled explicitly by use of e_L , the per unit emissions for surplus inventory at the end of the period. Similarly, the target emissions per unit is denoted e , the per unit emissions from the first (offshore) and second supply options are denoted e_1 and e_2 , respectively. Let $L(q)$ denote the expected overage given the offshore order quantity q , and $Q(q)$ the expected underage.

$$L(q) = E[(q - X)^+] = \int_0^q (q - x)f(x)dx,$$

$$Q(q) = E[(X - q)^+] = \int_q^\infty (x - q)f(x)dx$$

The expected total emissions given the offshore order quantity q , $E(q)$, is determined as

$$E(q) = e_1 q + e_2 Q(q) + e_L L(q)$$

Note that the model now considers emissions both from the first supply option, (the offshore supplier), the second supply option (which may be an onshore supplier), and from items in stock at the end of the selling period. The latter includes disposal of the unsold products.

The inventory management problem is to maximize the expected profit $P(q)$, defined as above, subject to the PCF constraint, $E(q) \leq B(q)$, where $B(q) = e(q + Q(q))$. Note that this PCF constraint concerns the expected emissions, and that the upper bound $B(q)$ is linear in the total order quantity ($q + Q(q)$) which corresponds to the total demand. (An alternative, for example, used in Song and Leng (2012) is to set a constant upper bound on the emissions independent of q , say, B . This is then analogous to a capacity constraint.) Under reasonable parameter values it is shown that the optimal offshore order quantity under the PCF constraint, q_{CF} is

$$q_{CF} = \begin{cases} q_{l1} & \text{if } q^* < q_{l1} \\ q_{l2} & \text{if } q^* > q_{l2} \\ q^* & \text{otherwise} \end{cases}$$

The lower and upper control limits, $q_{l1} < q_{l2}$, define the feasible region, and are obtained as the intersection points of $E(q)$ and $B(q)$. Note however that the lower limit q_{l1} might be non-existing, for example, if the condition $e_1 \leq e \leq e_2$ is not fulfilled. Recall that $q^* = F^{-1}(d/(d+c-z))$ is the unconstrained optimum to max $P(q)$ defined above.

Based on this analysis, Arkan and Jammernegg (2014) consider two situations for the second supply option; (i) an environmentally friendly but expensive onshore supplier (similar to Rosič and Jammernegg (2013) above) and (ii) a fast emergency transport option from the offshore supplier. The onshore supplier is characterized by lower per unit emissions than the offshore alternative (motivated by less transport emissions), i.e., $e_2 < e_1$. Conversely, fast emergency shipments from the offshore supplier suggests higher per unit emissions (and costs) than its regular shipments (e.g., air vs. sea) with $e_2 > e_1$.

For the onshore option with $q_{CF} = \min\{q^*, q_{l2}\}$, one can conclude that q_{CF} decreases if the per unit emissions e_1 , e_2 , or e_L increases, or if e (the per unit emission target) decreases. Thus, if the per unit emissions increase, or if a tougher emission target is introduced, the firm buys less from the offshore supplier, and more from the environmentally friendly onshore supplier. Recall that the model presumes that all demand is satisfied.

For the fast emergency transport option from the offshore supplier, the behavior of q_{CF} with respect to e_1 , e_2 , e_L , and e is the same as long as e_2 is smaller than e (i.e., the per unit emissions for emergency shipments are below the per unit target). In case $e_2 > e$, the behavior depends on the critical ratio $d/(d+c-z)$, and q_{CF} may either decrease or increase.

From a numerical study the authors make a number of observations about trade-offs between the sourcing options, costs, and emissions. For example, within large ranges of the emission and cost parameters, the alternative with an onshore supplier offers significant reductions in emissions with only small reductions in expected profits. Moreover, if the onshore option offers lower per unit costs than the emergency shipment option, it is better both from environmental and economic perspectives. On the other hand, if the per unit cost for the onshore option is much higher than for the emergency shipment option, onshoring may lead to both higher costs and emissions. The latter is due to the model requirement of satisfying all demands. To avoid using the expensive onshore option (which must be used if there are shortages) q_{CF} is increased significantly, which leads to more emissions for producing and transporting ($e_1 q_{CF}$), but also for handling and disposing of more units that are left over in inventory ($e_L L(q_{CF})$).

Other green inventory management literature based on the newsvendor framework includes Song and Leng (2012). They consider the classical newsvendor model under three types of carbon emission regulations; a mandatory carbon emission constraint, a linear carbon emissions tax, and a cap and trade system.

Choi and Chiu (2012) consider a newsvendor model for a risk averse fashion retailer where any items in stock at the end of the selling period is obsolete and wasted. They establish mean-variance (MR), and mean-downside risk (MDR) models and compare their levels of sustainability to the classical risk neutral retailer, which maximizes the expected profit. The considered measures of sustainability are: expected number of unsold items in stock, expected sales to expected overage ratio, rate of return on investment, and the probability of achieving a predetermined profit target. They find that for these measures, the risk averse MR retailer is more green than a risk neutral retailer.

Choi (2013) considers a dual-supply model in a newsvendor framework for a fashion retailer employing a quick response system. In contrast to Rosič and Jammernegg (2013) above, both supply options (i.e., orders both to the offshore and onshore suppliers) occur before the selling season starts. Between the time of the first ordering opportunity (with the offshore supplier), O , and the time of second order opportunity (with the local supplier), L , it is assumed that the fashion retailer can improve its demand forecast. The analysis shows how a properly designed per unit tax can be used to enhance the environmental sustainability by sourcing more (or solely) from the local (onshore) supplier with less emissions. However, the emissions are not modelled explicitly.

8.3.1.2 Multi-period Single-Echelon Models Considering Modal Choice and Shipment Consolidation

The literature on inventory management of multi-period single-echelon inventory systems is very large. However, there are relatively few papers on green inventory management approaches that explicitly consider emissions or environmental concerns. Issues emphasized in this emerging literature, so far, are modal choice and

shipment consolidation. This makes sense, as transportation is one of the major sources of emissions in logistics.

Hoehn et al. (2014) consider a single item, single-echelon, infinite horizon, periodic review inventory model, where replenishments are made in the beginning of each period according to an order-up-to-S (or base-stock) policy. Demand is assumed to be continuous and stochastic, and all unsatisfied demand is backordered. In this basic modeling context the authors study how carbon emission regulations can affect a firm’s choice of transportation mode for inbound deliveries. More precisely, the firm can choose between transport mode options with different constant lead-times ($L_i, i = 1, 2, \dots, I$), costs, and emission characteristics. The firm can only choose one option involving a single transport mode (i.e., terminal to terminal transport is assumed). The considered cost components for transport mode i are: a back-order cost per unit and time unit (p_i), a holding costs per unit and time unit (h_i), and purchase and transportation costs per unit (c_i). The holding and transportation costs depend on the emissions for transport mode i via an emission cost, c^e , per unit of emissions. This emission cost can reflect an emissions regulation, for example, in terms of a carbon tax. The emissions associated with shipping one unit on transport mode i , e_i , depend on the transportation distance, constant and variable emission factors, and load factors. The expected costs $C_i(S_i|c^e)$ for transport mode i , with base-stock level S_i , and emission cost c^e , can be expressed as

$$C_i(S_i | c^e) = h_i(c^e)[S_i - \mu(L_i + 1)] + (p + h_i(c^e))G_i(S_i) + c_i(c^e)\mu$$

where

$h_i(c^e)$ = holding cost per unit and time unit for transport mode i and emission cost c^e

$c_i(c^e)$ = transportation cost per unit for mode i and emission cost c^e

$f_i(x)$ = density function of the demand for $L_i + 1$ periods

$G_i(y)$ = loss function = $\int_y^\infty (x - y)f_i(x)dx$

μ = expected demand per period

The optimal base-stock level, S_i , that minimizes $C_i(S_i|c^e)$ coincides with the solution to the traditional newsvendor problem (see, for example, Axsäter 2006). The transport mode that minimizes the expected costs for a given emission cost, c^e , are easily obtained by comparing the cost-minimizing solutions for each transport mode.

$$\min_{i \in I} \left\{ \min_{S_i} C_i(S_i | c^e) \right\}$$

The authors investigate how the choice of transportation mode depends on the emission cost by deriving intervals for c^e where different modes are preferred. These intervals indicate how high a carbon tax needs to be in order for a certain transport mode to be selected. From a small numerical study, based on realistic values for cost parameters and emissions, they conclude that the emission cost typically needs to increase drastically for a greener transport mode to be preferred. This suggests

that emission taxes are blunt weapons for achieving emission reductions through modal shifts. On the other hand, introducing emission constraints that force a change may lead to significantly higher costs. However, the authors are careful to note that in practice many other issues outside their model may influence the choice of transportation mode.

Turning to issues of shipment consolidation and joint deliveries, Larsen and Turkensteen (2014) analyze a VMI (Vendor-Managed Inventory) system by jointly modeling shipment consolidation, routing, and retailer inventory decisions using a JRP (Joint Replenishment Problem) approach. A vendor with ample stock is supplying a product to a large number of geographically dispersed retailers. The objective is to minimize the total inventory and transportation costs. The retailers are assumed to be identical and uniformly distributed over a two-dimensional (circular) area, or a one dimensional line, for example, describing a transportation corridor. The retailers, experiencing Poisson-distributed demand, are grouped into zones, where each zone is replenished by joint deliveries on a single vehicle. Each retailer incurs holding and backorder costs and uses an order-up-to-S policy to replenish its inventory.

The replenishment orders from zone j accumulate at the vendor, and corresponding stock units are reserved and placed in a transportation bin. When the level V_j is reached (i.e., the bin is full) a dispatch is made (at the end of the considered time period). Hence, a quantity-based shipment release policy is used. The holding costs for units in the transportation bin are attributed to zone j . The transportation costs include a fixed cost per dispatch, a cost per distance unit traveled, and a fixed cost per retailer visited. As demand is stochastic, a shipment may contain replenishments to only a subset of the retailers in zone j . Because retailers are identical, it is easy to determine the probabilities for m retailers in zone j being replenished by a shipment. The expected length of a delivery route can then be estimated using continuous approximations. The detailed specification of the transportation costs enables an analysis of how the inventory decisions affect the vehicle utilization and transportation distances. Turkensteen and Larsen (2013) build on these results and in conjunction with an engine emission model they provide a method for evaluating the expected transport-related CO₂ emissions for the VMI system at hand. A numerical study illustrates that as the fixed dispatch costs increase, the CO₂ emissions decrease. This is a result of using shorter less frequent delivery routes (smaller zones) with increased load factor, and comes at the price of more inventory.

Shipment consolidation may be done in many different ways (the quantity-based policy above is just one example) and there is a large body of literature that focuses on inventory management of single-echelon systems using various types of shipment consolidation (or release) policies (e.g., Çetinkaya and Lee 2000; Axsäter 2001; Çetinkaya and Bookbinder 2003; Chen et al. 2005; Çetinkaya et al. 2006; Çetinkaya et al. 2008; Mutlu and Çetinkaya 2010; Mutlu et al. 2010; Kaya et al. 2012). These papers typically study inventory management at a vendor, which dispatches consolidated shipments to a number of retailers (the inventory management of these are not considered), with the objective to minimize holding and transportation costs. Emissions or environmental effects are in general not

explicitly evaluated in this literature. An exception is Merrick and Bookbinder (2010) that use simulation to investigate how three commonly used shipment release policies can affect transport emissions. However, arguably, many of the cost models in this existing literature could be extended to include evaluations of expected emissions, particularly if the transport emissions can be modelled analogous to the transportation costs, i.e., by a fixed component per dispatch and a variable component proportional to the number of units on the shipment.

Another stream of literature of interest from a green inventory management perspective is the one focusing on inventory management of perishable products. Extensive reviews are provided in Nahmias (2011) and Karaesmen et al. (2011). A perishable item is characterized by having a limited life span during which it has a constant value (or utility). When that life span ends the item loses its value and needs to be disposed of. This may fit many different types of products, but from an environmental perspective, food and pharmaceuticals are important examples where the disposal of outdated and wasted products may have a big financial and environmental impact, not only in terms of GHG emissions. The existing models for inventory management of perishable items (excluding the trivial special case of the newsvendor model) focus on cost minimization or profit maximization and do not, to our knowledge, explicitly consider emissions or environmental consequences. However, it is easy to incorporate evaluation of these sustainability issues as the analysis generally renders the expected number of perished items associated with certain inventory policy decisions. The challenge to reconcile the economic and environmental objectives and determine the best decision from a sustainable inventory management perspective still remains though. The perishable item literature is because of its complexity focused on inventory management of single-echelon systems. However, considering multi-echelon systems, as in Olsson (2010), is an interesting venue for future research in green inventory management.

8.3.2 Green Multi-Echelon Inventory Management

In multi-echelon inventory management, the scope is extended from managing a single stock-point, to jointly managing a system of connected inventory locations, typically, upstream and downstream in a supply chain. The simplest multi-echelon structure is a serial system where each inventory location has exactly one predecessor and one successor. In distribution of finished goods, the divergent structure, where each inventory location has one predecessor but many successors, is very common. Conversely, in manufacturing, assembly systems, where each inventory location can have many predecessors but only one successor is commonly seen. Managing a network of connected inventory locations clearly increases the complexity, but also the degrees of freedom and potential for green supply-chain solutions. The substantial literature on stochastic multi-echelon inventory management still contains few models that explicitly incorporate emissions or environmental consequences, but the field is emerging.

Stenius et al. (2016) consider green inventory management of a distribution system with a central warehouse supplying goods to a number of retailers (in accordance with a VMI agreement) using a time-based shipment consolidation policy with periodic shipment intervals. The central warehouse has access to inventory and point of sale information for the entire system in real-time through an integrated IT system. The free flow of demand information means that there are no incentives for batch ordering at the retailers. However, fixed costs for handling and shipping, together with ambitions to reduce transport emissions, create strong incentives for shipment consolidation and joint deliveries to groups of retailers. The presented model extends the work in Marklund (2011) by enabling exact evaluation of load-dependent non-linear shipment costs and emissions. A key result is the derivation of the probability distribution for the number of units on each shipment. Based on these results, a setting emphasizing the model's usefulness from a sustainability perspective is further analyzed. It involves capacitated dual transport options from the central warehouse to the retailers, and is motivated by industry applications. Transportation capacity can be reserved in advance at an intermodal shuttle train solution (or alternatively at a fleet of modern low-emission trucks). If this capacity is insufficient when a shipment is to be dispatched, truck transports available on demand (typically a more emission-intensive option) are used as a complement. The analysis, assuming Poisson demand, shows how to jointly optimize the reorder levels (at the warehouse and all retailers), the shipment intervals (to all retailer groups), and the capacity reservation quantities (for all shipments) so as to minimize the total expected costs. Emissions are taken into consideration by use of a side constraint on the total expected emissions or alternatively by introducing emission costs. The analysis is applicable to both single- and multi-item systems. A numerical example, based on realistic cost and emission data illustrates how the model can be used for evaluating the cost impact of managerial decisions to reduce emissions. It indicates that relatively large reductions of the expected emissions can be achieved without severe cost increases. However, minimizing the emissions may increase the costs significantly. For instance, reducing the CO₂ emissions by 24 % compared to the cost optimal solution only increases the expected costs by 3.5 %. To achieve this, the shipment intervals (time between shipments) are increased, and more capacity is reserved on the train, resulting in an additional 10 % of the total shipment volume to be moved from truck to train. The inventory is also increased to compensate for the longer lead times. On the other hand, minimizing the expected emissions leads to a maximum reduction of 34.5 % compared to the cost optimal solution, while this causes the expected costs to increase by 17.5 %.

Berling and Martínez-de-Albéniz (2015) use a continuous serial system (i.e., a serial system with infinite number of stages) to investigate the economic and environmental benefits of adjusting the speed at which a unit is transported through the system, based on the current inventory situation. This can be interpreted as the value of slow steaming or despeeding of the supply chain when the situation allows it. Applying the model to a road transport case study illustrates that substantial savings

in both cost and emissions can be attained by adjusting the speed to the inventory situation rather than using a fixed speed policy (savings of 7% and 20% respectively were recorded).

So far, there are few models that incorporate emissions associated with not satisfying customer demand on time, still in some cases these emissions may be quite significant and most relevant to consider. One area where the impact of insufficient service often is quite severe is in the distribution of spare parts. The parts are often quite small suggesting limited emissions associated with transportation, inventory holding, and warehousing. However, not delivering them promptly may have serious consequences on costs and emissions. The former is accentuated by an increasing use of service contracts with high penalty costs and liability clauses in case of insufficient service fulfillment. A related issue is the use of emergency shipments to reduce the impact of shortages and associated downtime costs commonly seen in practice.

Johansson and Olsson (2016) consider a model motivated by collaboration with a spare parts service provider in the dairy industry. In this case, failure to provide a spare part within a relatively short time limit after a machine breakdown leads to grave environmental and economic consequences. The reason is that the entire production batch, of, say, yogurt, must be discarded and the facility must be cleaned before production may be resumed. The analysis deals with a one-warehouse- N -retailer system and provides a method for evaluating and minimizing the expected costs by optimizing the base-stock levels at all facilities. The method also enables evaluation of the expected emissions associated with not satisfying the demand within the given time window.

As indicated above, when shortages occur it is often economically rational to use emergency shipments even though they are generally more expensive and emission-intensive than regular shipments. At least if they are supplied from the same location as regular orders. The increased emissions may be caused by use of faster and more emission-intensive modes of transportation (e.g., air instead of road or sea), or by reduced load efficiencies in vehicles used for emergency deliveries. One may interpret costs and emissions for emergency shipments as a consequence of not succeeding in satisfying customer demand on time through the regular system. Avoiding unnecessary use of emergency shipments is therefore a way towards green inventory management. A first step in this direction is to assure that the inventory control system provides the intended service. Berling and Marklund (2014b) use simulation to study this issue at a Scandinavian spare parts provider for agricultural machinery. The company's distribution system consists of a central warehouse (located in the south of Sweden) and a large number of retailers/dealers spread out across the Scandinavian countries. The objective is to investigate the potential of reducing total costs and transport emissions. This is done by simulating the system when applying the multi-echelon inventory control methods presented in Berling and Marklund (2013, 2014a) instead of the methods currently used by the company. The simulation study, encompassing a stratified sample of 106

representative items, shows that by using the reorder points obtained from the multi-echelon method, transport-related CO₂ emissions are reduced by 57 %, the inventory holding costs are down by 18 %, and the demand-weighted average fill-rate across retailers and items increased by 34 %. These results illustrate that avoiding unnecessary shortages by implementing inventory control methods with better precision can be a first low hanging fruit in achieving more sustainable inventory management in practice.

Another aspect, discussed above, is that many existing models for evaluation and minimization of expected costs have a potential for incorporating evaluation of emissions or environmental aspects to some extent. We make no attempt to review the multi-echelon literature from this perspective, but we would like to highlight two areas with apparent sustainability potential: the use of advance demand information, and systems that allow for lateral transshipments and/or include emergency/quick response stocks.

Use of advance demand information essentially means that customers place (firm) orders before they need the products. The time between the order placement and demand realization represents a time buffer that offers possibilities to reduce inventories and/or use greener but slower transportation options. The use of different shipping alternatives by Amazon is one example motivating the work in Chen (2001). Other examples from the multi-echelon inventory literature on advance demand (or advance order) information include Özer (2003), Gallego and Özer (2003) and Marklund (2006). To our knowledge the literature does not yet contain any sustainable inventory management models that explicitly consider advance demand (or advance order) information in conjunction with emissions or environmental consequences.

Inventory systems with lateral transshipments (sometimes referred to as complete pooling models) are characterized by multiple retailers sharing their inventory by agreeing to transship stock between them when needed. For a recent literature overview we refer to Paterson et al. (2011). From an emissions point of view, lateral transshipment systems offer interesting opportunities to combine short distance transshipments by environmentally friendly electrical or biogas vehicles, with long-distance consolidated shipments by diesel truck, train, or ship to a geographical region. A related system structure seen in practice is one with partial pooling, where designated support warehouses with quick response stocks offer local warehouses fast emergency deliveries to avoid shortages (e.g., Kranenburg and van Houtum (2009), Axsäter et al. (2013) and Howard et al. (2015)). In principle they offer the same possibilities to combine consolidated deliveries to a region with fast short-distance emergency shipments. The managerial complexity to coordinate decisions is reduced in these systems at the expense of reduced potential for inventory pooling. To our knowledge, no complete or partial pooling models that explicitly consider emissions are yet available in the literature.

8.4 Concluding Remarks About Findings, Practical Implications, and What Remains to be Done

A recurring finding throughout this chapter is that sustainable inventory management can offer opportunities to reduce emissions quite substantially (from a cost-minimizing solution) with relatively small increases in total costs. However, attaining solutions that minimize emissions may be costly.

Several case studies have shown through simulation of real data that companies can improve the cost and service performance of the inventory management system by using better inventory control methods. More recent studies illustrate that this finding can carry over to the environmental aspect as well. A common problem in practice is that the inventory management system does not deliver the intended service. This leads to additional shortages and if these shortages give rise to e.g., emergency shipments or goods being wasted, the additional emissions can be significant. Examples from work cited above show reductions of expected costs of 18% along with emission reductions of up to 57% linked solely to improved inventory control and better fulfillment of target service levels. This without involving changes to order quantities, shipment frequencies, mode of transport, shipment consolidation policies, etc. This illustrates a promising improvement potential of inventory management practices to simultaneously reduce both costs and emissions.

With respect to the studied regulatory systems that policy makers may invoke to reduce emissions, the conclusion from several models is that a cap and trade system is more attractive from a company perspective (less costly) than carbon taxes or systems with fixed emission caps. Moreover, indications are that complete modal shifts to greener transportation alternatives are difficult to attain by use of carbon taxes alone, unless they are extremely high. At the same time, other results suggest that multimodal transport solutions or dual-supply options may offer attractive compromise solutions.

A noteworthy finding is that most of the existing literature on green (or sustainable) inventory management is based on very simple inventory models, particularly the EOQ-model and the newsvendor model. More general inventory models that incorporate emissions and other environmental consequences are needed in order to offer adequate tools for practical use. The literature is growing but much remains to be done. Existing inventory models with pure cost or profit focus can be a good starting point, if the emissions structure and cost structure coincide.

Finally, we note that the practical use of any green inventory management method requires access to accurate emissions (and cost) data at appropriate levels of detail. To avoid suboptimization and achieve reductions in total costs and emissions for a supply chain, inventory management decisions should be considered in conjunction with transportation and production planning decisions, and strategic decisions such as network-configuration, modal shifts, etc. To facilitate this, standardization of emission measurements and calculations across different industries, companies, and activities that cause emissions (production, transportation, warehousing, etc.) are important. Otherwise, evaluating trade-offs and total effects become ambiguous.

Refinement and more widespread use of common tools for environmental impact calculations such as NTM^{CALC} by the organization NTM (Network for Transport Measures) are promising developments in this area.

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