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A sustainable inventory management model for closed loop supply chain involving waste reduction and treatment

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ABSTRACT

With the environmental concerns emerged in the last decade, the transition towards circular economy production models has become a top priority for industrialized countries. Retail supply chains however are still mostly referred to the linear "take-make-consume-dispose" model, which is recognized to be a largely unsustainable approach due to the implied unbalanced consumption of energy and resources and uncontrolled generation of waste. The development of new and more suitable decision models for supply chain management in compliance with the principles of circularity is thus an industrial need and an emergent research field. Based on a detailed analysis of the systemic criticalities in linear supply chain management models and on their inherent exposure towards decision biases leading to overproduction, this research proposes an original closed loop supply chain management model coherent with the product lifecycle approach and compliant with the 4Rs model adopted in EU regulations. Specifically, the model shifts towards reducing waste, by considering non-constant salvage value for the products at the end of the selling season, depending on their actual conditions. The proposed model is validated through a numerical application which demonstrates how the unscrupulous use of traditional stochastic inventory management models substantially hinders the sustainability of the supply chain, unless a reverse logistic channel and appropriate waste management policies are enforced. Comparing the linear and the closed loop models, by means of a numerical application, with the closed loop model the expected leftover inventory decreased of the 65%, while the expected lost sales increased of the 83.4%. The results obtained demonstrate the effectiveness of the approach proposed in analyzing the dynamics of supply chain management models, and performing scenario analyses on different configurations, thus obtaining useful insights for sustainable supply chain design.

The main contribution of the research is to incorporate the 4R into the newsvendor model, determining new optimality conditions that imply the overall reduction of waste because of a smaller quantity of products managed along the supply chain respect to the linear supply chain model, assuming that supply chain's actors are willing to accept a higher stockout risk in view of less inventory stocks. The results also show that the overall profits of the closed loop supply chain reduce of the 26.2% respect to the linear supply chain profit, which can be considered the 'cost' of circularity.

1. Introduction

In response to the urgent global climate emergencies threatening the preservation of the natural resources of our planet, the governments and institutions of industrialized countries have recently undertaken appropriate transition paths to lower the pressure of anthropic activities on the environment, according to the Circular Economy (CE) model. In the European Union (EU), the initial steps of implementing the framework of CE were undertaken since 2014, although the fundamental principles of circularity were present in EU regulations since the 70 s. In particular, the first action plan promoting the shift toward CE systems was adopted in 2018 (European Commission, 2018), while one year later the European Green Deal (2019) included, among its goals, the decoupling of economic growth from the use of natural resources. As such, transitioning toward CE means a radical change in the way products are designed, manufactured and disposed, and requires the

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development of new production paradigms and business models capable of balancing the legitimate profit objectives of private entities with the preservation of natural resources (Lewandowski, 2016). A top strategic priority in such regard is the establishment of circular supply chains as a sustainable alternative to the linear "take-make-consume-dispose" models, which are currently predominant. Such models are based on the use of inputs deriving from natural resources considered available in unlimited quantities, which is nowadays recognized to be a largely unsustainable approach, due to its implied unbalanced consumption of energy and resources and uncontrolled generation of waste. This situation can be clearly recognized considering the global production of primary raw materials, which was 22 billion tons in 1970, raised to 70 billion tons in 2010 (OECD, 2019), with a growth twice as fast as the global population during the same period. Similarly, the global resource extraction, which amounted at 7 gigatons in 1900, reached 89 gigatons in 2015 (Aguilar-Hernandez et al., 2021), while the global solid waste generation raised from less than 0.3 Mt. per day in 1900 to more than 3.5 Mt. per day in 2010, and it is expected to double in 2025 and triple by 2100 (Hoornweg and Bhada-Tata, 2012).

Such evidences arguably demonstrate how the mass production model introduced at the end of the 19th century and the establishment of supply chains oriented to profit maximization, has actually resulted in the development of unsustainable industrial systems. Indeed, such production paradigm, based on the maximization of production volumes to fully exploit the scale economies, is affected by substantial overproduction issues, and involves an unsustainable generation of waste, in the absence of appropriate management policies for end-of-life products. Unsustainable waste generation as a consequence of overproduction is thus a critical problem in contemporary supply chains which results in costly externalities burdening the population and society. In addition, in some specific industry fields, such as agrifood, construction, electric and electronics and fashion, overproduction phenomena and inadequate waste management practices not only generate a cost for the population but also have severe environmental and social impacts (Hicks et al., 2004, Meinlschmidt et al., 2018; Bukhari et al., 2018).

Based on the above considerations, this research provides an in-depth discussion of the supply chains dynamics which are at the basis of overproduction and surplus-creating processes, focusing in particular on the link between overproduction and waste management. The approach proposed highlights how the unscrupulous and widespread use of stochastic inventory management models (e.g. the "newsvendor" model) is a main cause of systemic criticalities in the supply chain, due to their inherent exposure towards biases in the management decision processes. The highly competitive nature of modern retail markets, for example, can easily induce retailers to maintain higher levels of product availability than required, therefore originating a consistent overstock which is seldom recovered at the end of the season. Such approach indeed allows for the obtainment of extra-profits since in linear supply chains (LSCs), the waste treatment costs of the overstocked products are externalities borne by the society. Contrarily, in the transition towards a closed loop supply chain (CLSC), the producer is charged with the waste treatment costs in coherence with the extended Original Equipment Manufacturer (OEM) responsibility principle, therefore, a reduction of the amount of waste produced and/or of the related treatment cost will improve the overall performance of the system. In such regard, industrial companies are currently implementing appropriate waste management policies in the general framework of the product lifecycle approach, concentrating their efforts on the establishment of reuse, recycle and recovery processes.

In general, the approach to waste reduction, reuse, recycle and recovery, known as the 4R model, which is at the core of the current EU waste hierarchy framework (Kirchherr et al., 2017), involves appropriate strategies to reduce the amount of waste generated by industrial production systems, as well as the implementation of suitable waste management processes in order to reuse the products at the end of their lifecycle or to recover the materials and the energy. A review of recent scientific literature on such topic, however, shows that the efforts of researchers and practitioners are mainly focused on the reuse, recycle or recovery processes while reducing the waste generated is a less considered topic.

This implies that LSC models are applied without incorporating the overproduction reduction strategies, with the consequence that the replenishment strategies are not optimized for this purpose and only response plans are adopted at the end of the selling season.

This is the first gap this research aims at addressing, by proposing a CLSC model that considers the value/cost of the fractions of sales and leftover inventory that can be reused/recycled/recovered at the end of the selling season as variables to take into consideration in optimizing the profit and, as consequence, the quantity of products to manage.

A second gap which is investigated in this research relates with the possibility of shifting from supply chain models in which the understock risk adverse behavior is enforced, to models that include a higher risk appetite in exchange for a more sustainable supply chain management.

For such purposes, the paper focuses on the application of stochastic inventory management models in a CLSC, and on their influence on the supply chain decision-making processes, to demonstrate how the implementation of circularity principles can actually lead to a reduction of waste generation. In particular, the approach proposed relies on an original formulation of a closed-loop newsvendor model whose implementation is considered in the general framework of the lifecycle approach and waste management practices enforced by current regulations.

Since we are not aware of mathematic formulations that model this supply chain management strategy, the willingness to demonstrate its validity justifies the current research.

The novelty of the approach proposed lays in the formulation of a comprehensive methodology for addressing the overproduction and waste generation problems of modern supply chains, and on the demonstration of the existence of an unexploited waste reduction potential. The mathematic formulation of the newsvendor problem is consequently modified to incorporate the 'reduce/reuse/recycle/recover' behavior and the optimal quantity of products to manage is determined in this condition.

The main contribution of this work to the advancement of knowledge in the addressed research field is the identification of the conditions under which the CLSC is a viable solution and, above all, the consequences of adopting it, such as the increased risk for understock, the reduced leftover inventory, the management of lower quantity of products along the chain that justify the reduction in the overall supply chain profit. The aim of the paper is to implement the waste management hierarchy and thus, out objective is not to identify the conditions under which the End of Life (EOL) treatments (reuse or recycle or recover) are profitable or not, but exemplify what its optimized implementation implies in terms of profit and costs for the supply chain actors, as well as in terms of acceptance of higher stockout costs in view of lower leftover inventory.

The remainder of the paper presents a comprehensive literature review on the circular supply chain models, considering the overproduction and waste generation problems. Subsequently the 3rd section reports the methodology formulated, which is validated in the 4th section through a numerical application. The results are presented and extensively discussed in the 5th section. The 6th section reports the main insights and limitations of the study proposed and, finally, the conclusions are presented in the last section.

2. Literature review

Circular supply chain (CSC) management, defined as the integration of the circular economy principles into the supply chain management scope (Farooque et al., 2019; Tseng et al., 2022; Mishra et al., 2023; Xiong et al., 2022), has recently become a prominent research field. In particular, the design and development of reverse logistic systems for appropriately managing end-of-life products has revealed a fundamental element to achieve economic and environmental sustainability and to address the waste management problems originated by industrial supply chains oriented to mass production (Chen et al., 2021; Milios, 2021, Baars et al., 2021; Mishra et al., 2023). In the manufacturing industry, the development of "green" operations to improve the overall sustainability of the SC has also gained a substantial relevance with the introduction of the Waste Electrical and Electronic Equipment (WEEE) Directive issued by the EU (European Union 2012). The concept of CLSC promoted by this regulatory framework encompasses the management of the forward and reverse logistics to maximize value creation over the entire life cycle of a product. To such regard, Life Cycle Assessment (LCA) models support the WEEE reverse logistics in quantifying the potential environmental impacts of a product or system, from resource extraction through manufacturing and use, to final disposal (see Rocha and Penteado, 2021 for an example of LCA of WEEE reverse logistic systems). An essential element of such an approach relates to the implementation of appropriate value recovery processes, through activities like collection, repair, recycling, remanufacture, and reuse (Guide et al. 2003). The recent literature on CSC however is essentially focused on waste recovery processes, while waste reduction practices have received much less attention.

2.1. *Waste generation and the 4R model*

Referring to the problem of waste generation, the CE model envisages the closure of loops in industrial ecosystems by applying the "reduce-reuse-recycle" (3R model) formulated in the last century. Such model has been extended in the last decade by introducing the energy "recovery" process thus becoming the 4R model, which is the foundation of the current EU waste hierarchy framework (Kirchherr et al., 2017). Other researchers further extended the R-based circularity framework beyond the 4Rs, thus proposing the 5Rs (Gharfalkar et al., 2015), 6Rs (Yan and Feng, 2014), and 9Rs models (Sihvonen and Ritola, 2015, Potting et al., 2017). Such models consider the minimization of the amount of waste generated as a necessary complementary action to waste treatment in a generalized CE strategy, since by reducing waste some crucial objectives of the sustainable development can be reached, such as the minor consumption of natural resources, the limitation of transport activities, etc.

In such regard a recent research stream within the interdisciplinary field of waste management highlights overproduction as a main responsible of waste generation (Chaboud and Daviron, 2017; Mourad, 2016; Pedersen et al., 2015; Vulcano and Ciccarese, 2017). Overproduction refers to the excess of supply over demand, which results in providing more products than the market can actually receive, thus originating unsold leftover inventories. Referring to the supply chain literature (Shingo, 1989), two types of overproductions can be identified: early and quantitative. The former refers to the creation of products prior to their need, while the latter to the creation of more products than required. The problem of overproduction is currently regarded as substantial criticality of modern supply chains, particularly in the fashion industry, in construction and in agrifood chains. Some luxury brands, for example, are well known to systematically landfill or incinerate the leftover stock at the end of the season, in the convincement that this is the most cost-effective way to protect exclusivity and avoid devaluing the brand image. In the electronics market, the surplus inventory is very common due to technological or functional obsolescence that renders older products less attractive for the consumers (Roberts et al., 2023). Referring to the agrifood chains, an enlightening study recently published by Messner et al. (2021), confirms the findings of a substantial body of research and reveals 'food overproduction' and 'food surplus' to be significant factors in food waste generation at a global level and in economically developed countries (Hall et al., 2009; Hiç et al., 2016; Aiello et al., 2015a; Aiello et al., 2015b). In particular, overproduction in the final stage of the supply chain – i.e. packaged products wasted in the retail stores – is considered among the worst sources of waste because it can trigger several additional inefficiencies such as unnecessary manufacturing, handling, transportation, and more possibilities for product loss and defects, etc.

2.2. *Customer satisfaction and overproduction*

Focusing on the causes of overproduction, a first consideration is that mass production systems mostly rely on the make-to-stock supply chain architecture (Wortmann 1983), involving push decision processes based on predicted market demand. Since predictions are not 100 % accurate, additional (safety) inventories are generally maintained to protect against the variability of market demand, thus originating overproduction and unsold stocks, ending up in waste. Although the inherent uncertainty of market forecasts is an intrinsic element of supply chain management, not necessarily it has to result in a systemic cause of overproduction. A closer look at the supply chain management practices currently enforced in retail supply chains, in particular, reveals that some decision biases often affect the management processes and lead to excess inventories. In such regard, several researchers actually highlighted how production management decisions are often based on the belief that higher production volumes allow for a better utilization of resources (Gupta & Jain, 2013), while retailers frequently maintain more inventory than actually required to achieve higher levels on-shelf availability. Phenomena such as the bullwhip effect fall into this context, with the result that the increase in the leftover inventory is perceived at all stages of the supply chain (see de Kok et al., 2005, for a case study related to the electronics components).

In modern competitive markets indeed, ensuring customer satisfaction and long-term loyalty can easily lead managers to overestimate the cost of lost sales against the cost of leftover inventories, particularly when waste management costs are not charged to the supply chain. Moreover, distribution contracts typically include product availability clauses resulting in penalties for partial or total non-delivery of orders, thus pushing suppliers to carry over-protective inventories in order to meet very high service-level targets (Mena et al., 2014). In addition, common commercial practices such as overstocking of short shelf-life foods to create the impression of abundance as well as removing products from the shelves due to damaged packaging even if their functionality is not affected can easily result in consistent amounts of surplus and waste.

2.3. *Applicability of the newsvendor model in the real competitive contexts*

The consequences of decision biases in inventory management practices typically enforced in traditional mass production supply chains are discussed in the stream of literature focused on behavioral aspects of supply chain decision making. It is well proven, in particular, that in a real-world situation, managers' decisions often deviate from the optimal solution provided by the classical newsvendor model (Nagarajan and Shechter, 2014, Schweitzer and Cachon, 2000). More recently Yamini (2021) provided a detailed review on the behavioral perspective of newsvendor ordering decisions, while Pournader et al. (2023) demonstrated how decision-makers in a supply chain increase their order quantities when the objective is to maximize profit and reduce their order quantities when the objective is to minimize loss. Actually, the traditional newsvendor model refers to LSCs, where the cost of overproduction is only related to the salvage value of the product, without explicitly taking into account the waste treatment processes and related costs, which are considered external to the SC. The constant salvage value assumption is common in the scientific literature, and the consequent issues have been discussed by several researchers (Ding et al.,2002, Fisher and Raman, 1996, Perakis and Roels, 2008 Terwiesch and Cachon, 2006). Alternative salvage value models have been proposed by Cachon and Kok (2007) who first showed that assuming a constant salvage value could induce companies to place too big orders. An alternative model in such regard is to consider the salvage as the output of a clearance pricing decision rather than a fixed value. In the supply chain management literature, the link between overproduction and inventory control has been studied mainly referring to the possibility of reselling excess inventory on secondary markets (e.g., Lee and Whang 2002). For example, Mostard and Teunter (2006), extended the traditional newsvendor model to include the possibility of receiving items returned by customers that are in good enough condition to resell in the primary market. Flexible ordering and return policies for retailers in cases of uncertain market demand have been also studied by Pasternack (1985), Emmos and Gilbert (1998) and Donohue (1996), focusing on the optimal product return contracts from the point of view of the manufacturer, while Padmanabhan and Png (1997) studied the consequences of ordering flexibility provided by return contracts in retail. Referring to this research stream, the approach here proposed originates from some common assumptions but differentiates from the aforementioned approaches since post-consumer goods are here considered as waste that can be reused, remanufactured or recycled into new products within the general CE model. In particular, the model proposed in this research falls within the scope of management decisions for CLSCs, considering the tradeoffs between new production and waste treatment operations thus embracing the whole scope of alternatives considered in the 4R model, namely: waste reduction, product reuse, as well as remanufacture and recycle possibilities. The returns policies considered in this study occur at the end of a limited selling season due to demand uncertainty and to the retailer's overstocking of inventory.

2.4. Product recovery to implement closed loop supply chain

This stream of literature refers in particular to the supply chain models considering waste treatment and/or disposal activities. In such regard, the approach proposed links to the scientific literature that considers the waste disposal cost, with the aim of aligning stochastic inventory management policies to the principles of circularity. In particular, Savaskan et al. (2004) addressed the problem of determining the right reverse supply chain for collecting used items from customers in the CLSC. Savaskan's research has been further extended by assuming that retailers and third parties competitively collect used products (Huang et al., 2013) and by considering the third party as a single channel in the reverse supply chain (Maiti and Giri, 2015; Su et al., 2019). Relevant contributions have also been provided by Hasanov et al. (2013) who proposed a four-level CLSC problem involving the disposal cost, energy, and transportation cost and by Dwicahyani et al. (2020) who considered waste disposal for unrecoverable returned items and a rework process in a CLSC consisting of a supplier, a manufacturer and a retailer. A relevant closed-loop newsvendor model was further proposed by Bhattacharya et al. (2006), considering multi-period decisions and investigating channel coordination assuming new and remanufactured products are perfect substitutes. Additional relevant research contributions have been also provided by Wu and Wu, (2010) that studied pricing strategies in a self-selection waste disposal mode in a closed-loop system and by Kundu and Chakrabarti (2018) who proposed a reverse logistic model for a single-stage system where the items that were not recoverable would be disposed of as waste after a sorting or disassembling process. Chuang et al. (2014) discussed CLSC models for a high-tech product with a short life-cycle and volatile demand under alternative reverse channel and collection cost structures and investigated the impacts of collection cost structures and implementations of product take-back laws on the manufacturer's choice of reverse channel structures. Finally, Jauhari et al. 2020 proposed a CLSC model consisting of three parties (manufacturer, retailer and collector) involving remanufacturing and refurbishing processes and Jaber et al. (2014) proposed a mathematical model for a two-echelon system with a consignment policy to coordinate a manufacturer and a retailer and utilized waste disposal for managing unrecoverable items.

In Table 1 the most relevant studies among those mentioned in the review of the literature are reported highlighting their main features, and the main differences with our model evidenced.

3. Methodology

As we stated in the literature review, the topic of the waste management optimization models is a well-established research field with a huge amount of examples. However:

- some models adapt the linear supply chain models including the management of EOL product at the end of their life;
- other models specifically address the CLSC considering constant salvage values, and even when this is not, they however don't allow to set the supply chain parameters (quantity of products to be reused, recycled, recovered) to optimize the profit.

In such context, the model proposed introduces a new perspective in which different salvage values are set depending on the destination of the products at the end of the selling season, which means that waste management models are not only devoted to EOL products but also to leftover inventory. A profit optimization model is then defined that determines the quantities/values of the expected lost sales, leftover inventory and not recoverable products, in which the optimality conditions imply that the supply chain actors are willing to accept a higher stockout risk and lower profits with respect to the LSC, in view of lower leftover inventory and to reduce waste management costs. The reduction in profits is actually the 'cost' of the waste management that in our model is charged by the supply chain itself and not by the society.

In the remainder of the paper, the following notation will be used.

Nomenclature

c: unit production cost, the cost at which the products are purchased by the retailer,

p: unit selling price, the price at which the products are sold at the target market,

s: unit salvage value, the price at which the leftover products are sold,

c_u: unit understock cost, the cost incurred for the lost sales,

c_o: unit overstock cost, the cost to store surplus products,

cf: critical fractile, an indicator of the level of service,

Q: the quantity of products manufactured to satisfy the demand during the season,

$S(Q)$: the amount of products sold at the market during the season, a function of the quantity Q stocked at the beginning of the season,

$I(Q)$: leftover inventory, i.e. the number of products that remain unsold at the end of the season, a function of the quantity Q stocked at the beginning of the season,

k_{S1}: the fraction of sales which can be reused,

k_{S2}: the fraction of sales which can be recycled,

k_{S3}: the fraction of sales which can be transferred to energy recovery process,

k_{I1}: the fraction of leftover inventory which can be reused,

k_{I2}: the fraction of leftover inventory which can be recycled,

k_{I3}: the fraction of leftover inventory which can be transferred to energy recovery process,

V_{reuse}: unit value of product reuse,

$V_{recycle}$: unit value of product recycling,

$V_{recover}$:unit value of energy recovery,

$c_{collect}$: unit cost to collect the products from the consumers and inspect them,

x:random variable representing the product demand,

$f(x)$: probability density function of demand,

$F(x)$: cumulative distribution function of demand.

Table 1
Relevant literature contributions of the models addressing the optimization of the supply chain management including reusing recovering and recycling policies and differences with respect to the present paper.

Reference	Main features of the reference	Comparison with the present study
Nagarajan and Shechter, 2014	They showed that the Prospective Theory (PT) cannot be used to predict the people ordering decisions as in the low profit regime PT predicts that decision makers would order less than the optimal newsvendor order quantity, and more in the high profit regime	As it evidences how leftover inventory can be managed by recurring to reuse, recycle and recovery, the proposed model can provide the decision makers with a clear view about the products management, motivating them to adhere to the optimal quantity.
Schweitzer and Cachon, 2000	They considered the newsvendor model and showed that usually the decisions about how much order deviate from the optimal quantity of the newsvendor model, trying to minimize the absolute difference between the chosen quantity and realized demand. As a consequence, the decision makers order less than the optimal newsvendor order quantity in high profit regime, and more in the low profit regime.	
Pournader et al. (2023)	They investigate whether risk aversion, risk seeking, loss aversion, or prospect theory could explain the ordering decisions in multiechelon supply chains, using controlled laboratory experiments, and found that if the profit maximization is the objective the loss aversion behavior increases, while if the loss minimization is the objective ordering less quantities is the choice.	As it allows us to determine the value of reused, recycled and recovered products, as well as the value of the inventory, lost sales and profits achievable, the proposed model allows us the modeling of the different risk appetites of the supply chain actors.
Ding et al.,2002, Fisher and Raman, 1996, Perakis and Roels, 2008 Terwiesch and Cachon, 2006	These research models hypothesize constant salvage value	The proposed model considers different costs for the reused, recycled and recovered products, providing practitioners with a clear view of the costs incurred by the supply chain actors in implementing CLSC models with respect to LSC
Lee and Whang 2002	They considered reselling excess inventory on secondary markets	In considering the 'reuse' policy, the proposed model incorporates the possibility of selling the leftover inventory in secondary markets, but it goes beyond estimating the quantity of products to destine to this market to optimize the CLSC profit.
Mostard and Teunter (2006)	They extended the traditional newsvendor model to include the possibility of receiving items returned by customers that are in good enough condition to resell in the primary market	In considering the 'recovery' and 'recycle policy, the proposed model incorporates the possibility of collecting the products from the customers to sell them in secondary markets (included the energy market), but it goes beyond estimating the quantity of products to destine to these markets to optimize the CLSC profit.
Savaskan et al. (2004)	They addressed the problem of determining the right reverse supply chain for collecting used items from customers in the CLSC.	
	Hasanov et al. (2013)	They proposed a four-level CLSC problem involving the disposal cost, energy, and transportation cost. The results they determined emphasized that accounting for energy, transportation and disposal costs in supply chain modelling increases the sustainability of a production-inventory system due to the strong interdependence of the three costs on one hand, and their relationship to the environment on the other hand
The proposed model goes beyond the optimization of a supply chain managing EOL products, providing the practitioners with insights to set new supply chain parameters to actually implement a CLSC, such as the value of reused, recycled and recovered products and the related quantities.	Dwicahyani et al. (2020)	They considered waste disposal costs for unrecoverable returned items and a rework process in a CLSC consisting of a supplier, a manufacturer and a retailer. items which cannot be perfectly recovered will be categorized as refurbishable items and then sold to the secondary market at a reduced price.

3.2. Model formulation

In this section the basic elements of the traditional newsvendor model are initially recalled, then the model developed is extended for the CLSC and the related implications are discussed. The standard newsvendor model refers to a traditional LSC where the manufacturer sells the product via a retailer to consumers and no collection or recovery activities are implemented for products at the end of their lifecycle, as depicted in Fig. 1. in this model, the producer issues the amount Q of products to the retailer. The amount S(Q) of products is sold on the target market, while I(Q) products remain unsold at the end of the selling season. The units produced and purchased by the retailer are thus either sold or salvaged at a constant value at the end of the season.

Assuming there is no defective production, the corresponding expected profit $E(\pi)$ can thus be calculated as a function of the quantity ordered, based on the newsvendor model (Edgeworth 1888, Raz and Porteus, 2006) as:

$$E[\pi] = (p-c)^{*}E[S(Q)] - (c-s)^{*}E[I(Q)] \tag{1}$$

where $E[S(Q)]$ and $E[I(Q)]$ respectively represent the expected number of products that are sold on the target market, based on the market requests taking into account the demand variability, and the expected amount of

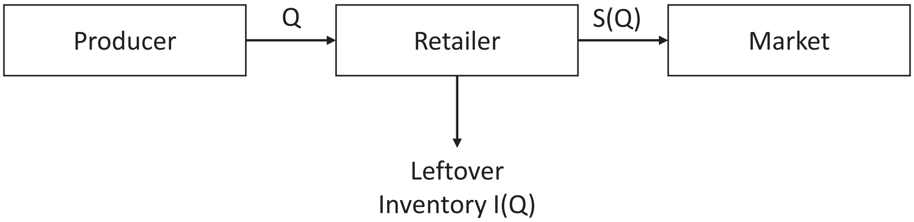

Fig. 1. LSC model.

leftover inventory, defined as:

$$E[S(Q)] = \int_0^Q xf(x)dx + Q(1 - F(Q)) \tag{2}$$

$$E[I(Q)] = \int_0^Q (Q - x)f(x)dx \tag{3}$$

In equation (2), the quantity $Q(1 - F(Q))$ represents the Expected Lost Sales $E(LS(Q))$.

The following relation links the produced (supplied) quantity to the expected sales and expected leftover inventory.

$$Q = E[S(Q)] + E[I(Q)] \tag{4}$$

The problem faced by the newsvendor when determining the optimum quantity to order is two dimensional: on one side excessive stocks will result in unsold products reducing the profit, while on the other hand insufficient stocks result in unsatisfied demand. In the newsvendor model these two competing forces are balanced using the critical fractile (*cf*), calculated through the marginal overstocking and understocking cost, according to eq. (5).

$$cf = \frac{c_u}{c_u + c_o} \tag{5}$$

The critical fractile is directly related to the "optimal" amount of inventory to purchase, which is determined as the inverse cumulative function of the demand calculated in the cf, as in Eq. (6).

$$Q = F^{-1}(cf) \tag{6}$$

where F is the cumulative function of the demand (see for reference Porteus 1990; Snyder and Shen, 2019).

Contrarily to a traditional forward-only supply chain, in a CLSC, the manufacturer not only sells the original products to consumers in the forward channel but also collects the product at the end of their lifecycle for remanufacturing and recycling through a reverse logistic channel. Hence, the choice of an appropriate reverse channel structure influences the manufacturer's overall profit in the CLSC. For example, some high-tech manufacturers (e.g. Samsung) collect the used consumer electronic products directly from consumers, by offering a free mail-back option and a permanent drop-off option. Still in the hi-tech market, other manufacturers collect the used product from consumers through collection kiosks their retailers, as in the case of the GreenFill Program enforced by Sony, while others collect the used product from consumers through a third-party logistic operator as in the case of LG Electronics Recycling Program. A detailed discussion of the structure of reverse logistic channel can be found in Yang et al (2020).

In this research, we consider a CLSC model where the retailer buys Q products from the producer at the unit cost c. The customers buy the products from the retailer at a market price p, while products that reach the end of their lifecycle are directed towards suitable reuse, recycling or energy recovery processes. In particular, the products that remain unsold at the end of the season (i.e. leftover inventory) can be either reused, recycled or their energy can be recovered, while used products are collected at the unit collecting cost c_{collect} before being treated as waste.

The constant salvage value model is thus replaced with a suitable reuse, recycle or energy recovery process in coherence with the extended OEM responsibility principle and 4Rs model without any external cost borne by the society (see Hom, 2024). The supply chain hence involves suitable processes to appropriately manage end-of-life products. In such a situation, the leftover inventory is constituted by products that have reached the end of their lifecycle without undergoing a use phase, while sold products undergo a use phase and must be collected at the end of their lifecycle and inspected to determine their appropriate reuse, recycling, or energy recovery process.

The corresponding SC model considered is depicted in Fig. 2.

Following the already mentioned 4Rs model (Hom, 2024), in the model proposed it is assumed that all the products reaching the end of their lifecycle are directed in different fractions towards reuse, material recovery (recycle) processes or energy recovery plants. In general, the fractions (K_{S1}, K_{S2}, K_{S3}) of collected products that are addressed towards reuse, recycle and recovery processes will most likely be different from the fractions (K_{I1}, K_{I2}, K_{I3}) of leftover inventory addressed to the same processes, because sold products have undergone a use phase which may have altered their original features and functionalities.

Based on such assumptions, the expected profit referred to the closed supply chain scheme given in Fig. 2 can be calculated through eq. (7).

$$\begin{aligned} E[\pi] = &(p - c)E[S] - cE[I] + k_{I1}E[I]V_{reuse} + k_{I2}E[I]V_{recycle} + k_{I3}E[I]V_{recover} \\ &- c_{Collect}E[S] + E[S]k_{S1}V_{reuse} - E[S]k_{S2}V_{recycle} - E[S]k_{S3}V_{recover} \end{aligned} \tag{7}$$

where $k_{I1}E[I]V_{reuse} + k_{I2}E[I]V_{recycle} + k_{I3}E[I]V_{recover}$ is the value of the leftover inventory generated by the waste recovery strategy, while $E[S]k_{S1}V_{reuse} - E[S]k_{S2}V_{recycle} - E[S]k_{S3}V_{recover}$ is the value of the sold products collected at the end of their life cycle.

In eq. (7), implicit signs are considered for the reuse, recycling, or recover costs, meaning that their contribution to the profit can be positive if the recovered value is higher than the waste processing cost, or negative in the opposite case. Consequently, the fraction of products that can be treated according to the waste hierarchy options considered in the 4R model affect the decision of the optimal quantity. For example, waste treatments typically involve a cost which overcomes the value of the recovered products, while product reuse, when possible, generates a positive contribution. According to such a model, an additional waste management cost is borne by the supply chain which can be calculated by summing up the remanufacturing cost and quality improvement cost of remanufacturing for both the products sold on the market and the leftover inventory. Based on the eq. (7), the total value resulting from treating the products at the end of their lifecycle can thus be calculated as:

$$TV_{wm} = TV_{reuse} + TV_{recycle} + TV_{recover} \tag{8}$$

where:

$$TV_{reuse} = k_{I1}E[I]V_{reuse} + E[S]k_{S1}V_{reuse} = V_{reuse}(k_{I1}E[I] + E[S]k_{S1}) \tag{9}$$

$$TV_{recycle} = k_{I2}E[I]V_{recycle} + E[S]k_{S2}V_{recycle} = V_{recycle}(k_{I2}E[I] + E[S]k_{S2}) \tag{10}$$

$$TV_{recover} = k_{I3}E[I]V_{recover} + E[S]k_{S3}V_{recover} = V_{recover}(k_{I3}E[I] + E[S]K_{S3}) \tag{11}$$

The CLSC model depicted in Fig. 2 has to be read considering the

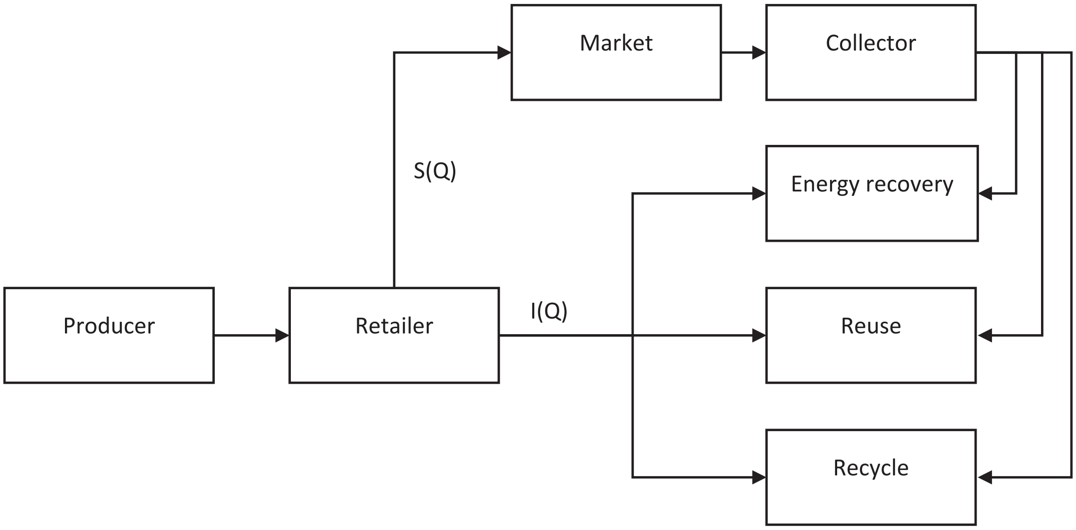

Fig. 2. CLSC model.

waste management hierarchy for which the priorities from the most to the least important are: reduce, reuse, recycle and lastly recover. The supply chain optimization model presented attempts to implement this hierarchy and thus the different values resulting from treating the products are not matter of trade-off, in order to decide whether it is effective to implement one or another strategy for the EOL products. Thus, in the proposed model the assessment of the profitability of the approach is verified on the overall supply chain profit.

4. Numerical application

In this section, in order to validate the proposed methodology, a numerical application is proposed, which is referred to a realistic situation in order to demonstrate how the replacement of the fixed salvage value with the waste treatment costs of a CLSC actually reduces the profit of the manufacturer and lowers the production volume, which ultimately result in a more ethical cost distribution and a more sustainable production volume. Adapting the data used in Jauhari et al 2020 case study, we considered the following price/costs: p = 988.77, c = 800, s = 500.

The products are sold on a market with a normally distributed demand with average value (μ) equal to 10,000 and std.dev (σ) equal to 2,500.

Under these hypotheses, the Expected Lost Sales ($E[LS(Q)]$), the Expected Sales ($E[S(Q)]$) and the Expected Leftover Inventory ($E[I(Q)]$) can be determined based on the formulation of the newsvendor problem as:

$$E[LS(Q)] = \sigma^{*}L(z(Q)) \tag{12}$$

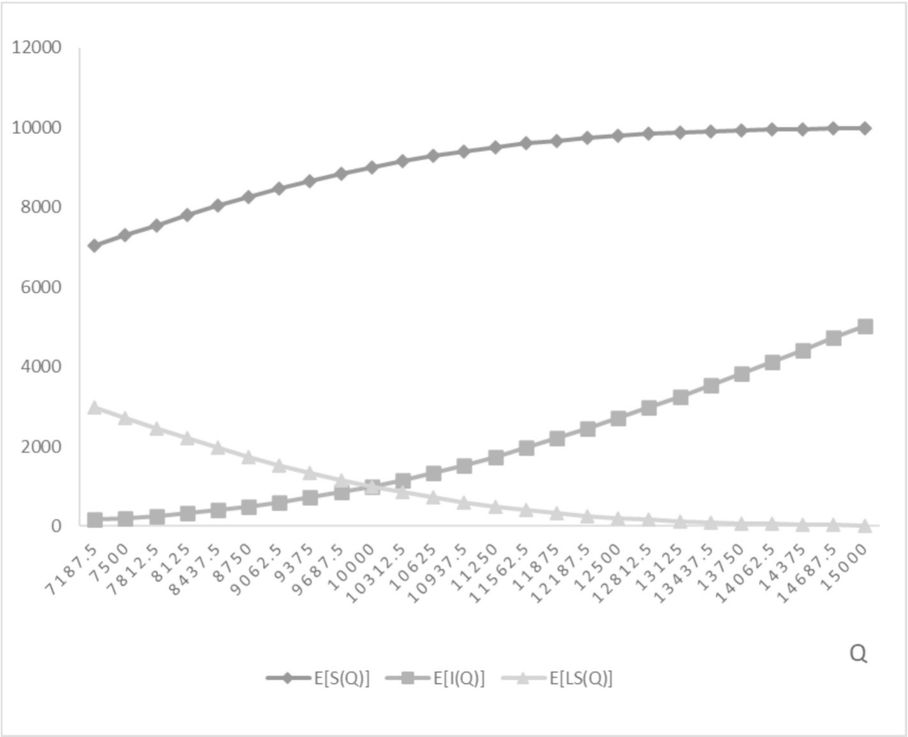

Fig. 3. Exp. sales, exp. inventory and exp. lost sales as function of the quantity.

$$E[S(Q)] = \mu - E[LS(Q)] \tag{13}$$

$$E[I(Q)] = Q - E[S(Q)] \tag{14}$$

where $z = \frac{x-\mu}{\sigma}$ is the Normal standard variable and $L(z(Q)) = Normdist(z, 0, 1, 0) - z^{*}(1 - Normsdist(z))$ represents the stockout probability (see King 2018), which can be easily calculated using a spreadsheet.

In such a setting, the E[S(Q)], E[I(Q)] and E[LS(Q)] are represented as a function of the quantity in Fig. 3.

In this figure, it can be seen that in the classic newsvendor model applied to the LSC the expected lost sales decrease as the amount of managed products increase, while the expected leftover inventory increases. In the following, by comparing the optimum decision in a LSC and in a CLSC, we aim at showing how different assumptions regarding the treatment of sold and unsold end-of-life products affect the decisions concerning the optimum quantity to order. Referring to the LSC, it is assumed that decision processes are governed by the Newsvendor model, therefore the optimum quantity is equal to 9,277 pieces corresponding to a critical fractile equal to 0.3862, calculated according to eq.5. The corresponding expected Supply Chain profit (E[π]) can be determined based on Eq. (1); the Expected Overstock Cost ($E[OC(Q)]$) can be determined as:

$$E[OC(Q)] = c_o{}^{*}E[I(Q)] \tag{15}$$

and Expected Lost sales Cost (E[LSC]) can be determined as:

$$E[LSC(Q)] = c_u{}^{*}E[LS(Q)] \tag{16}$$

The results are given in Fig. 4.

In this fig. it can be seen that the expected value of the understock decreases as the amount of stocked products increases, while the expected overstock costs increases, also according to Fig. 3. This implies that an optimal amount of products to stock exists that optimizes the total profit. For the analysis of the CLSC, we consider the possibility of reusing the products at the end of their lifecycle when their functionalities are preserved or treating them in recycling or energy recovery facilities otherwise. Reused products will preserve a residual (salvage) value, while recycling and energy-recovery processes will involve a corresponding cost. The CLSC scenario can thus be considered the extension of the LSC where the constant salvage value model is replaced by the closure of the supply chain. An additional cost is borne for treating the products at the end of their lifecycle, while the leftover inventory can be reused at same constant salvage value employed in the LSC model.

Based on Jauhari et al, 2020, the values considered for calculation are given in Table 2.

From Table 2, it is evident that reusing implies a reward for the supply chain, while recycling and recovering result in a cost to be charged by the supply chain. For the numerical application, we assume that the fraction of products that can be reused, recycled or directed to an energy recovery process is different for the products that have undergone a use phase and for the leftover inventory. In particular, it is assumed that unsold products (i.e. leftover inventory) at the end of the season preserve their function and maintain a salvage value (similar to the value of a product sold in a secondary market), therefore being suitable for a full reuse policy. Contrarily, sold products, reaching the end of their lifecycle after a use phase, do not involve any advanced waste management process therefore allowing only for an energy recovery process (which is the worst option in the EU waste hierarchy) after collection. The collection cost $c_{collect}$ is thus considered only for products sold and it is assumed equal to 15 (Jauhari et al, 2020). With such assumptions, this closure scenario is coherent with a traditional product not designed according to the lifecycle design principles which preserve a salvage value as long as its functionalities are present, or it can be only processed for energy recovery, thus generating a disposal cost (see Table 3).

The corresponding E[π] as well as the costs of the leftover inventory I (Q), disposal cost and lost sales LS(Q) functions for the CLSC re given in Fig. 5.

In Fig. 5, the costs/revenues of the CLSC are shown to highlight their trend with the increase in the amount of stocked products. In particular,

Table 2
unit values of product reuse, recycle and recover in the scenario considered.

V_{reuse}	$V_{reclycle}$	$V_{recover}$
+20	−15	−8

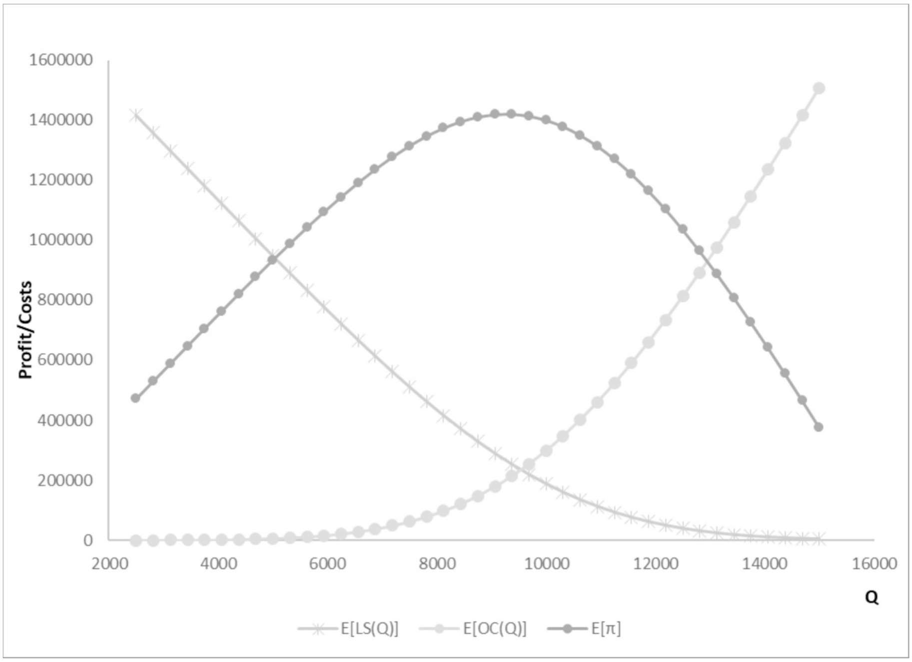

Fig. 4. newsvendor profit and costs for the LSC.

Table 3
assumed waste treatment possibilities of leftover inventory and sold products.

	Leftover Inventory			Sold Products		
	Reuse	Recycle	Recover	Reuse	Recycle	Recover
Fraction (%)	100 %	0	0	0	0	100 %

the lost sales costs decrease, while the leftover inventory costs and disposal costs increase. The overall effect on the profit is that an optimal quantity to stock can be found. Referring to the CLSC scenario, the maximum expected profit equal to 1,047,601.27 is achieved for an order quantity of 7,670 pieces.

5. Results and discussion

The results of the numerical application discussed in the previous section are reported for both the linear and the closed loop SC in Table 4. The comparison shows that the optimum order quantity is equal to 9,277 pcs for the LSC, while in the CLSC it reduces to 7,670 pcs., with a percent decrease of 17.3 %. However, the reduction in the exp. Sales is only 13.6 % while the reduction of the leftover inventory is approx. 65 %. Contrarily, the value of exp. Lost sales increases in the CLSC of 83.4 %. (Table 5).

The comparison of the results in the two cases considered shows that when the supply chain members are charged with the waste treatment cost, the optimum quantity reduces, thus reducing the amount of waste generated. The numerical application shows how charging the waste management costs to the supply chain members, the optimum quantity transferred to the market reduces, thus reducing the overproduction effect. This shows how a "sustainable" supply chain is thus characterized by a lower production volume, a relevant reduction in the leftover inventory generated, and by an increased exposure to lost sales. In addition, by analyzing different waste treatment scenarios, it can be shown that by implementing more advanced waste management processes (i.e. reducing the waste treatment costs) the production volume increases as well as the overall profit of the supply chain.

The corresponding profits in the two scenarios considered, reported in the table below, show that in the optimum conditions, a sustainable CLSC will achieve 73.8 % of the LSC profit; the expected overstock decreases of 7 %, while the expected understock increases of 83 %. The profit reduction can be regarded as the "cost of circularity", which is borne by the society in a LSC.

The results clearly show how charging the waste management costs to the supply chain members, the quantity of products transferred to the market reduces, thus reducing the overproduction effect. This essentially means that the optimum quantity in the LSC is overestimated as a consequence of a bias in the calculation of the critical fractile, which in the numerical application proposed is equal to 0.386. The optimal quantity calculated according to Eq. (6) balances the costs of losing sales with the cost of holding additional inventory. A straightforward consideration of Eq. (6) is that assuming symmetric demand distributions, when *cf* is higher than 0.5 the expected profit-maximizing the order quantity is greater than the average demand, while if the *cf* is lower than 0.5, then the order quantity is lower than the average demand. It thus is a common practice (see Schweitzer and Cachon, 2000) to define "high profit products", those products having a *cf* higher than 0.5, and "low profit products" the products with a *cf* lower than 0.5. Typical examples of high-profit products include media and fashion

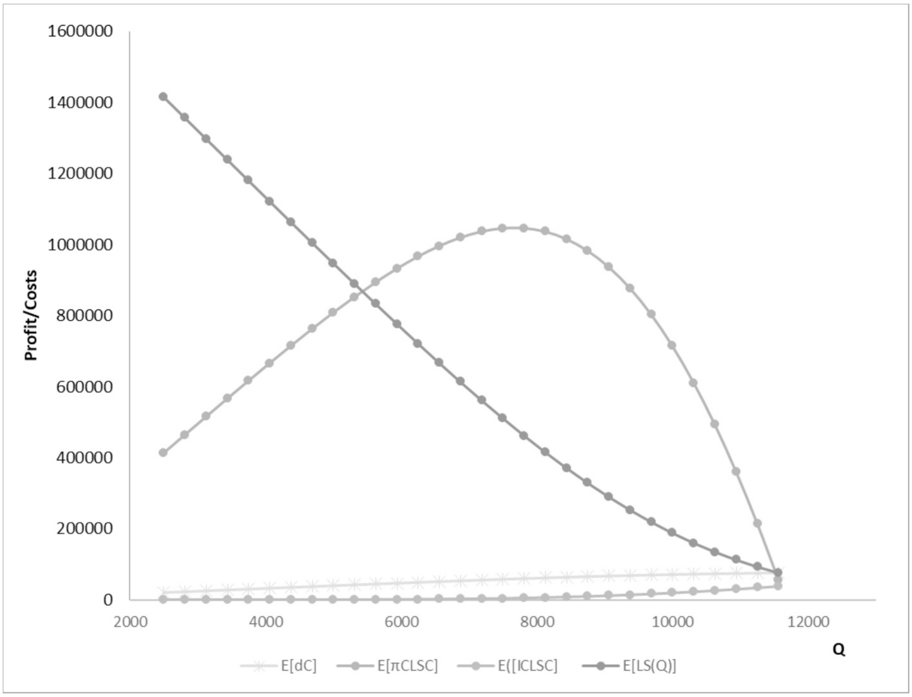

Fig. 5. supply chain profit, expected lost sales, expected disposal cost and expected leftover inventory for the CLSC model.

Table 4
Comparison of the results for the LSC and CLSC.

	Opt. Quantity	exp. Sales	Exp. Leftover inventory	Exp. Lostsales	Reused Items	recycled Items	energy recovered items
LSC	9,277	8,600	677	1,400	0	0	
CLSC	7,670	7,433	237	2,567	237		7,443
	−17.3 %	−13.6 %	−65.0 %	83.4 %			

Table 5
Comparison of the costs and profit for the LSC and for the CLSC.

	Exp. Profit (E [π])	exp. Overstock cost (E[OC])	exp understock cost (E[LSC])	exp. Collection cost (E[$C_{collect}$])	exp reused value (TV_{reuse})	exp. Recycled cost ($TV_{recycle}$)	exp. Energy recovery value ($TV_{recover}$)	overall waste management cost (TV_{wm})
LSC	1,420,187.51	203,182.55	264,329.94					
CLSC	1,047,601.27	189,352.28	484,514.14	111,499.64	4,733.81	0	− 59,466.48	− 47,299.36
	−26.2 %	−7%	+83 %					

apparel, while low-profit products are functional products such as computers.

The corresponding managerial insight is that holding a little amount of stock for products with low margins is better since excessive inventory is more costly than lost sales, while holding more inventory for products with high margins is better because lost sales are more costly than excess inventory. As the numerical application shows, LSC delivering high profit products are structurally exposed to overproduction issues. In addition, it can be shown that in the Newsvendor model, when the uncertainty in the forecasted demand increases (i.e. the standard deviation of forecasted demand increases), the optimal order quantity will always increase. It is fairly recognized in the scientific literature that the difference between high and low value products actually influences the attitude of the decision maker introducing a "demand chasing" bias in the convincement that ordering more inventory would allow for more sales and profits. Such behavior eventually results in oversupplying the market with excess inventory that will be discounted or discarded at the end of the season. In practice, the consideration that high inventory levels generate the potential for more sales and profits induces a stockout-averse decision approach which leads to higher stocking decisions compared to a neutral decision maker. This over-cautious approach towards the risk of customer loss or market share reduction has been discussed by Schweitzer and Cachon (2000) who demonstrated how a stockout aversion in the decision maker preferences leads to defining an inventory level that is higher than the profit-maximizing quantity of a neutral decision maker.

Based on the considerations above, the proposed application demonstrates how the volume calculated through the standard newsvendor model with a constant salvage value is significantly higher than the production volume obtained in a CLSC including the waste treatment processes and related costs. In other words, the newsvendor model involves an inherent overproduction effect compared to a "sustainable" supply chain model. The problems related to the constant salvage value assumption in the newsvendor model are known to the scientific literature, in particular referring to the determination of excessive order quantities in clearance-pricing scenarios (see e.g. Cachon and Kok (2007)). The issues related to the over-simplification of the salvage value in the newsvendor model, however, have been rarely addressed in scientific literature, despite their relevance in supply chain decisions models. In such regard, the closure of the supply chain through a reverse logistic channel allows us to overcome the issues related to a fixed salvage value and allows us to implement more realistic processing options for the leftover inventory at the end of the season and for end-of-life products. The results of the numerical application proposed clearly show how underestimating the salvage value leads to increased production volumes, and, consequently, higher waste generation thereby affecting the overall sustainability of the supply chain. The CLSC model discussed in this paper substantially modifies the formulation of the original newsvendor decision model, replacing the constant salvage value with a more complex and realistic evaluation of the value of products at the end of their lifecycle. The resulting reduction of the production quantity allows for the reduction of the waste generated, while the closure of the supply chain with reuse, recycle and energy recovery processes complies with the waste hierarchy and 4R model.

The application proposed demonstrates how the widespread use of stochastic inventory management methods such as the well-known "newsvendor" model for high profit products is a main responsible of unsustainability of the supply chains. In fact, the proposed model showed as the over-simplistic assumption of a fixed salvage value in the newsvendor model results in over-estimating the critical fractile thus leading to biased decisions. Instead, the possibility of differentiating the salvage value based on a more conscious identification of the real product conditions allows the supply chain actors to manage EOL products as ready to use (eventually in a secondary market), recycle them after treatment, or recover them for the energy industry.

As a consequence of this, the model allowed us to highlight another aspect of the optimum production volume obtained through the newsvendor model, which is higher than the "sustainable" production quantity obtained in a CLSC, and exposes the supply chain to overproduction issues resulting in substantial externalities burdening the society. Instead, our model's optimum quantity is respectful of the 4R model and reaches the objective of waste reduction other than of reuse and recycle. Therefore, by not taking explicitly into consideration the treatment of end-of-life products and the related costs, the newsvendor is not compliant with the principles of circularity driving the transition processes of industrialized countries.

Although some of these issues have been actually discussed in scientific literature, a systematic review of such elements in terms of the general sustainability of the supply chain with a quantitative analysis of the potential benefits constitutes an element of novelty of the proposed approach and methodology.

6. Insights and limitations of the study

The results from applying the proposed model suggest that valuable insights can be gained. First, transitioning from the LSC to the CLSC involves reducing the number of products managed and accepting lower profits in exchange for fewer overstocks. This shift also requires a willingness to accept higher stockout risks, which can be offset by a commitment to more sustainable practices. It is not a matter to decide whether to implement one or another policy based on the profitability of the investment, but to implement le waste management hierarchy at the best of our possibilities.

The sustainability of the supply chain strategies is something the supply chain's actors must support by themselves, and in this respect the proposed study attempted at enforcing more conscious behaviors relating to the replenishment process.

Secondly, organizing the collection and reusing/recycling/recover of leftover/used products implies to involve other actors to put into practice the activities needed, promoting specific contracts to manage the relationships.

Moreover, in the long term, stocking less amounts of products may lead to a new supply–demand equilibrium with the increase of the prices, allowing the supply chain's actors to increase their profits.

Limitations of the study relate to the quality of the products, which is considered infinite, perfect and deterministic, while in some contexts this hypothesis can't be considered satisfied. This is the case of fresh products, like fruit and vegetables, whose initial shelf life can vary from product to product due to the inherent variability of the ripeness at the harvesting time, making that the residual shelf life of the products entering the cold chain has to be considered a stochastic variable. In addition, even cold chain-related variations of the environmental parameters (as temperature, humidity, etc) during the storage and transportation activities may affect the quality of fresh products, leading to an uncontrolled quality decay.

With regard to fresh products, their management has gained the interest of the researchers for some time now. So, for example, the authors published some papers (see Aiello et al., \2015a, Aiello et al., 2015b; Aiello et al., 2014c) that investigated the way in which food surplus can be managed, adapting the 4R principles to the food sector and considering the food donation —both for the purpose of the human or animal feeding- as a way to avoid the disposal of still edible products.

Another category of products with finite life are the products subject to rapid obsolescence, like fashion products whose lifespan is very limited and that are usually destined to the landfill.

In this regard, extensions of the proposed model may relate to incorporating imperfect quality and finite life of the products managed.

Moreover, the coordination aspect of the management of a CLSC should be addressed to determine the optimality conditions of a centralized approach and share the revenues among the supply chain's actors.

Thus, another possible extension of the present research may relate to the study of the coordination mechanisms that can prompt the supply chain's actors to promote waste management policies along the supply chain.

7. Conclusions

With the increased environmental concerns that emerged in the last decades, the implementation of the CE principles has become a top priority for industrialized countries. In such regard, the adoption of the 4Rs model in the EU regulations is currently driving the transition from LSC to CLSC featuring a reverse logistic channel along with appropriate waste management and reduction strategies. The supply chain management models currently enforced in industry, however, have been developed for LSCs, thus resulting in biased decision and unsustainable overproduction. Based on such considerations, this paper proposes an original decision model designed for CLSC involving a reverse channel and appropriate reuse, recycle and energy recovery processes for end-of-life products. The numerical validation of the model demonstrates how the methodology proposed can be employed for performing scenario analyses on different waste treatment strategies and related costs, thus obtaining useful insights also for sustainable supply chain design in coherence with the principles of the Lifecycle Approach.

Besides contributing to the stream of the decision models for CLSC, the findings obtained demonstrate that when the waste management costs are charged to the producer, according to the extended OEM responsibility principle, not only the externalities reduce, but the entire supply chain will deliver a lower quantity of products on the market, thus reducing the overproduction issues. These findings suggest that, without altering the fundamental characteristics of current supply chains decision models, systemic overproduction issues will eventually affect industrial supply chains, comprising their sustainability due to the related generation of wastes.

Referring to the scientific literature on CLSC, the proposed model can be further extended considering the quality issues in the production process and the presence of defective products in the supply chain, as well as introducing more advanced waste collection policies and treatments. For example, the investment in collection efforts can be considered to increase the number of returns thus justifying the employment of an increasing convex function. The total disposal cost of the collector can be determined by considering the number of items disposed of and the cost of disposing of them, therefore, different revenue-distribution schemes can be evaluated in order to balance the profit functions of the CLSC, in order to discuss the related coordination opportunities.

CRediT authorship contribution statement

Giuseppe Aiello: Writing – original draft, Investigation, Conceptualization, Funding acquisition, Validation, Methodology, Writing – review & editing. **Cinzia Muriana:** Writing – review & editing, Funding acquisition, Investigation, Conceptualization, Methodology, Data curation. **Salvatore Quaranta:** Writing – review & editing, Methodology. **Islam Asem Salah Abusohyon:** Methodology, Investigation, Writing – review & editing, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

References

Aguilar-Hernandez, G.A., et al., 2021. Global distribution of material inflows to in-use stocks in 2011 and its implications for a circularity transition. J. Ind. Ecol. 25 (6), 1447–1461.

Aiello, G., Enea, M., Muriana, C., 2015a. “Alternatives to the traditional waste management: food recovery for human non-profit organizations.”. Int. J. Oper. Quantitative Manage. 21 (3), 215–239.

Aiello, G., Enea, M., Muriana, C., 2015b. “The expected value of the traceability information.”. Eur. J. Oper. Res. 244 (1), 176–186.

Aiello, G., Enea, M., Muriana, C., 2014. “Economic benefits from food recovery at the retail stage: an application to Italian food chains.”. Waste Manag. 34 (7), 1306–1316.

Baars, J., et al., 2021. Circular economy strategies for electric vehicle batteries reduce reliance on raw materials. Nat. Sustainability 4 (1), 71–79.

Bhattacharya, S., Daniel, V., Guide Jr, R., Luk Van Wassenhove, N., 2006. Optimal order quantities with remanufacturing across new product generations. Prod. Oper. Manag. 15 (3), 421–431.

Bukhari, M.A., Carrasco-Gallego, R., Ponce-Cueto, E., 2018. Developing a national programme for textiles and clothing recovery. Waste Manag. Res. 36 (4), 321–331.

Chaboud, G., Daviron, B., 2017. Food losses and waste: Navigating the inconsistencies. Glob. Food Sec. 12, 1–7.

Cachon, G.P., Kok, A.G., 2007. How to (and how not to) estimate the salvage value in the newsvendor model. Manuf. Serv. Oper. Manag. 9 (3), 276–290.

Chen, X., et al., 2021. Does R&D intensity promote the adoption of circular supply chain management? evidence from China. Ind. Mark. Manag. 99, 153–166.

Chuang, C.-H., Wang, C.X., Zhao, Y., 2014. Closed-loop supply chain models for a high-tech product under alternative reverse channel and collection cost structures. Int. J. Prod. Econ. 156, 108–123.

de Kok, T., et al., 2005. Philips electronics synchronizes its supply chain to end the bullwhip effect. Interfaces 35 (1), 37–48.

Ding, X., Puterman, M.L., Bisi, A., 2002. The censored newsvendor and the optimal acquisition of information. Oper. Res. 50 (3), 517–527.

Donohue, K. “Supply contracts for fashion goods: Optimizing channel profits.” The Wharton School, University of Pennsylvania, Philadelphia, PA (1996).

Dwicahyani, A.R., et al., 2020. Inventory model optimisation for a closed-loop retailer-manufacturer-supplier system with imperfect production, reworks and quality dependent return rate. Int. J. Services and Oper. Manage. 35 (4), 528–556.

Edgeworth, F.Y., 1888. The mathematical theory of banking. J. R. Stat. Soc. 51 (1), 113–127.

Emmos, H., Gilbert, S.M., 1998. The role of returns policies in pricing and inventory decisions for catalogue goods. Manag. Sci. 44 (2), 276–283.

European Commission (2018), “Environment, circular economy, implementation of the circular economy action plan”, available at: https://ec.europa.

eu/environment/circular-economy/pdf/new_circular_economy_action_plan.pdf (Accessed December 2023).

European Green Deal (2019), available at: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/delivering-european-green-deal_en; accessed (Accessed December 2023). a.

Farooque, M., et al., 2019. Circular supply chain management: a definition and structured literature review. J. Clean. Prod. 228, 882–900.

Fisher, M., Raman, A., 1996. Reducing the cost of demand uncertainty through accurate response to early sales. Oper. Res. 44 (1), 87–99.

Gharfalkar, M., et al., 2015. Analysis of waste hierarchy in the European waste directive 2008/98/EC. Waste Manag. 39, 305–313.

Guide, Daniel R, V., Harrison, Terry P., Van Wassenhove, Luk N., 2003. The challenge of closed-loop supply chains. Interfaces 33 (6), 3–6.

Gupta, S., Jain, S.K., 2013. A literature review of lean manufacturing. Int. J. Manage. Sci. Eng. Manage. 8 (4), 241–249.

Hall, K.D., et al., 2009. The progressive increase of food waste in America and its environmental impact. PLoS One 4 (11), e7940.

Hasanov, P., et al., 2013. Closed-loop supply chain system with energy, transportation and waste disposal costs. Int. J. Sustain. Eng. 6 (4), 352–358.

Hiç, C., et al., 2016. Food surplus and its climate burdens. Environ. Sci. Tech. 50 (8), 4269–4277.

Hicks, C., et al., 2004. A functional model of supply chains and waste. Int. J. Prod. Econ. 89 (2), 165–174.

Hom, Kevin. "Circular Economy: The 4Rs reduce-reuse-recycle-recover." *IOP Conference Series: Earth and Environmental Science*. Vol. 1402. No. 1. IOP Publishing, 2024.

Hoornweg, D., Bhada-Tata, P., 2012. A global review of solid waste management. Urban Development & Local Government Unit World Bank, Washington, District of Columbia.

Huang, M., et al., 2013. Analysis for strategy of closed-loop supply chain with dual recycling channel. Int. J. Prod. Econ. 144 (2), 510–520.

Jaber, M.Y., Zanoni, S., Zavanella, L.E., 2014. A consignment stock coordination scheme for the production, remanufacturing and waste disposal problem. Int. J. Prod. Res. 52 (1), 50–65.

Jauhari, W.A., et al., 2020. A closed-loop supply chain model with rework, waste disposal, and carbon emissions. Oper. Res. Perspect. 7, 100155.

King, P.L., 2018. "Understanding safety stock and mastering its equations. APICS Magazine.

Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: an analysis of 114 definitions. Resour. Conserv. Recycl. 127, 221–232.

Kundu, S., Chakrabarti, T., 2018. Impact of carbon emission policies on manufacturing, remanufacturing and collection of used item decisions with price dependent return rate. Opsearch 55 (2), 532–555.

Lee, H.u., Whang, S., 2002. The impact of the secondary market on the supply chain. Manag. Sci. 48 (6), 719–731.

Lewandowski, M., 2016. Designing the business models for circular economy—Towards the conceptual framework. Sustainability 8 (1), 43.

Maiti, T., Giri, B.C., 2015. A closed loop supply chain under retail price and product quality dependent demand. J. Manuf. Syst. 37, 624–637.

Meinlschmidt, J., Schleper, M.C., Foerstl, K., 2018. Tackling the sustainability iceberg: a transaction cost economics approach to lower tier sustainability management. Int. J. Oper. Prod. Manag. 38 (10), 1888–1914.

Mena, C., et al., 2014. Causes of waste across multi-tier supply networks: cases in the UK food sector. Int. J. Prod. Econ. 152, 144–158.

Messner, R., Johnson, H., Richards, C., 2021. From surplus-to-waste: a study of systemic overproduction, surplus and food waste in horticultural supply chains. J. Clean. Prod. 278, 123952.

Milios, L., 2021. Towards a circular economy taxation framework: expectations and challenges of implementation. Circular Economy and Sustainability 1–22.

Mishra, A., et al., 2023. Servitization in the circular supply chain: delineating current research and setting future research plan. Manag. Environ. Qual. An Int. J. 34 (4), 1035–1056.

Mostard, J., Teunter, R.u., 2006. The newsboy problem with resalable returns: a single period model and case study. Eur. J. Oper. Res. 169 (1), 81–96.

Mourad, M., 2016. Recycling, recovering and preventing "food waste": competing solutions for food systems sustainability in the United States and France. J. Clean. Prod. 126, 461–477.

Nagarajan, M., Shechter, S., 2014. Prospect theory and the newsvendor problem. Manag. Sci. 60 (4), 1057–1062.

Padmanabhan, V., Png, I.PL., 1997. Manufacturer's return policies and retail competition. Mark. Sci. 16 (1), 81–94.

Pasternack, B.A., 1985. Optimal pricing and return policies for perishable commodities. Mark. Sci. 4 (2), 166–176.

Pedersen, K.B., Land, B., Kjærgård, B., 2015. Duality of health promotion and sustainable development: perspectives on food waste reduction strategies. J. Transdisciplinary Environ. Studies 14 (2), 5–18.

Perakis, G., Roels, G., 2008. Regret in the newsvendor model with partial information. Oper. Res. 56 (1), 188–203.

Porteus, Evan L. "Stochastic inventory theory." Handbooks in operations research and management science 2 (1990): 605-652.Potting, José, et al. "Circular economy: measuring innovation in the product chain." Planbureau voor de Leefomgeving 2544 (2017).

Raz, G., Porteus, E.L., 2006. A fractiles perspective to the joint price/quantity newsvendor model. Manag. Sci. 52 (11), 1764–1777.

Pournader, M., et al., 2023. Decision bias and bullwhip effect in multiechelon supply chains: risk preference models. IEEE Trans. Eng. Manag.

Roberts, H., et al., 2023. Product destruction: exploring unsustainable production-consumption systems and appropriate policy responses. Sustainable Prod. Consumption 35, 300–312.

Rocha, T.B., Penteado, C.S.G., 2021. Life cycle assessment of a small WEEE reverse logistics system: case study in the Campinas Area, Brazil. J. Clean. Prod. 314, 128092.

Savaskan, R.C., Bhattacharya, S., Luk Van Wassenhove, N., 2004. Closed-loop supply chain models with product remanufacturing. Manag. Sci. 50 (2), 239–252.

Schweitzer, M.E., Cachon, G.P., 2000. Decision bias in the newsvendor problem with a known demand distribution: experimental evidence. Manag. Sci. 46 (3), 404–420.

Shingo, S., 1989. A study of the toyota production system: from an industrial engineering viewpoint. Productivity Press, Cambridge, MA.

Sihvonen, S., Ritola, T., 2015. Conceptualizing ReX for aggregating end-of-life strategies in product development. Procedia CIRP 29, 639–644.

Snyder, L.V., Shen, Z.-J., 2019. Fundamentals of supply chain theory. John Wiley & Sons.

Su, J., et al., 2019. A green closed-loop supply chain coordination mechanism based on third-party recycling. Sustainability 11 (19), 5335.

Terwiesch, Christian, and Gerard Cachon. "Matching supply with demand: an introduction to operations management." (2006).

Tseng, M.-L., et al., 2022. Healthcare industry circular supply chain collaboration in Vietnam: vision and learning influences on connection in a circular supply chain and circularity business model. Int. J. Log. Res. Appl. 25 (4-5), 743–768.

Vulcano, G., Ciccarese, L., 2017. Food Wastage: a systemic approach for structural prevention and reduction. Synthesis Report 267, 2017.

Wortmann, J.C., 1983. A classification scheme for master production scheduling. Efficiency of Manufacturing Sys. 101–109.

Wu, Di, and Chunyou Wu. "Research on Manufacturer's Product Pricing Model under Waste Self-Selection Disposal Mode." 2010 International Conference of Information Science and Management Engineering. Vol. 2. IEEE, 2010.

Xiong, Yu., et al., 2022. Game changer or threat: the impact of 3D printing on the logistics supplier circular supply chain. Ind. Mark. Manag. 106, 461–475.

Yan, J., Feng, C., 2014. Sustainable design-oriented product modularity combined with 6R concept: a case study of rotor laboratory bench. Clean Techn. Environ. Policy 16, 95–109.

Yang, L., Yijuan, Hu., Huang, L., 2020. Collecting mode selection in a remanufacturing supply chain under cap-and-trade regulation. Eur. J. Oper. Res. 287 (2), 480–496.

Yamini, S., 2021. Behavioral perspective of newsvendor ordering decisions: review, analysis and insights. Manag. Decis. 59 (2), 240–257.