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A circular economy with tax policy: Using collection channels and returns to mitigate distortions in steel production and recycling ☆

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ABSTRACT

The purpose of this research is to show how taxation of intermediate items produced from virgin and recycled materials negatively impacts closed-loop supply chain (CLSC) results (labor, capital, returns, outputs, prices, profits, and dead-weight-loss). It offers remedies to alleviate tax inefficiencies. After formulating upstream and downstream production functions and recycling process, a Stackelberg game framework is analytically solved and data from steel industry and automobile stimulus program in the US are used to obtain numerical results. The results show that an optimum collection channel along with endogenous consumer return behavior can improve outcomes and reduce inefficiencies stemming from output taxation. The principal policy implication is that American, Chinese, Canadian, and German governments' tax incentive programs applied to items produced from recyclables are a sound strategy in the way of spurring their circular economies, improving environmental sustainability, and reducing economic loss.

1. Introduction

Governments intervene into markets, impact choices of consumers and firms, and affect supply chain outcomes by implementing price, quantity, quality, and environmental regulations. Examples of such regulations concern end-of-life or used product collection, recycling, resource conservation and recovery, reuse amounts in manufacturing new products, subsidy, tax, and greenhouse gas emission restrictions. By implementing these regulations, legislators aim to encourage sustainable circular economies in order to reduce the environmental impact of used products, save energy, propel sustainable business, and achieve targets in the waste pyramid of reduce, reuse, recycle, energy recovery, and landfill (De Giovanni and Ramani, 2024).

While quantity regulations (weight/mass-based legislation involving collection and reuse amounts) in CLSC frameworks have been extensively studied (e.g., Atasu et al., 2009; Toyasaki et al., 2011; Esenduran et al., 2017; Tian et al., 2020), a growing stream of research investigates the impact of price regulations involving taxation and subsidy on supply chain outcomes (He et al., 2019; Li et al., 2020a,b; Liu et al., 2021; Mahmoudi et al., 2021; Yu et al., 2023; Zhu et al., 2023). This paper contributes to the literature of tax regulations in CLSCs.

It has been debated by the CLSC stakeholders and policy makers whether new products made from recycled materials should be provided tax credits. Some countries (e.g., the USA, China, Canada, and Germany) have already given tax incentives to firms which use a mixture of virgin and recycled materials in producing new products. However, the implications of taxation on CLSC outcomes (prices, outputs) and the benefits of tax incentives on CLSC performance (profits, social welfare) have not been extensively studied in the literature.

After examining these issues theoretically, an application germane to steel industry in the context of circular economy is investigated to quantify the impact of taxation and tax incentives on the CLSC outcomes. Steel is chosen as the subject of this study because it is the most recycled material in comparison to paper, plastic, aluminum, and glass in the US and Europe. In the context of steel recycling, end-of-life or old vehicles are examined because they are the largest source of recycled steel and provide more than 13 million tons of steel annually in the US. Recycling of steel from automobiles is estimated to save enormous amount of energy, equivalent to power 18 million homes every year. Furthermore, it provides environmental benefits and saves natural resources. For example, a new steel produced from a recycled content requires 60 percent less energy and reduces CO2 emissions by 58 percent compared to production from virgin materials. Also, recycling a single car can save more than 2500 lbs. of iron ore, 1400 lbs. of coal, and 120 lbs. of limestone (see The Institute of Scrap Recycling Industries, https://www.isri.org/recycled-commodities/ferrous).

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This work contributes to the CLSC literature by addressing the following crucial questions and their ramifications in the context of the steel industry:

- How does output taxation influence firms' strategies and economic performance of a CLSC in the steel industry?
  Because tax is an extra cost, it should affect the outcomes and profitability in CLSCs. However, which strategies are affected and how much it impacts economic activity and performance in the steel sector are the new research questions which will be addressed. This paper will analytically prove and numerically quantify that output taxation in the steel CLSC distorts all Stackelberg equilibrium prices and outputs and increases welfare loss at an increasing rate.
- How could the negative effects of output taxation be alleviated in the steel sector?
  After characterizing and quantifying the negative impacts of taxation, a novel question arises: what are the operational and tactical remedies to be implemented in CLSCs to mitigate the negative impacts? This paper offers new findings and shows that the tax distortions in the sector can be alleviated by *(a)* an optimal collection channel choice which involves a direct 3rd-party collection and *(b)* endogenous return behavior which encompasses providing monetary incentives to end-users.
- Does output taxation affect end-user returns in the reverse steel supply chain?
  While it is understood that taxation in CLSCs should affect firms' decisions and profits, it is not obvious whether it impacts the consumers' return decisions. If it does, then this should further impact prices and profits. This paper analytically and numerically shows that taxation will change the number of returns, and hence the CLSC performance.
- Is exogenous or endogenous return better for the steel CLSC?
  While there are different behaviors for used-product returns, it is valuable to know which one is applicable in the steel industry in order to initiate appropriate return programs and offer incentives accordingly. This paper proposes a unique endogenous return program applicable to the steel CLSC and shows that firms can further increase their profits under endogenous returns.
- Who should collect the used products under taxation in the steel industry?
  While this question has been examined for other industries, it is the first time it is posed for the steel CLSC. From logistics and operational perspectives collection channel matters. CLSC outcomes and profits usually depend on the collection channel. This paper shows that third-party direct collection provides higher profits to the firms in the steel supply chain.
- How do labor and wages impact CLSC decisions and strategies in the sector?
  While labor affects production function and wages impact marginal and average production costs, their roles on CLSCs have not been examined in the literature. This paper theoretically and numerically reveals how wages and labor affect CLSC strategies in the steel sector.

This article embeds a rich set of assumptions into the steel CLSC and contains several novelties. It examines steel recycling and production in a CLSC context, investigates implications of taxation in the industry, and quantifies the changes in steel and finished steel prices with respect to changes in tax rates. To our knowledge, this is the first study examining the steel CLSC. First, it explicitly specifies recycling and production functions to show how raw and recycled items are utilized to produce an intermediate product in the steel CLSC. Second, it examines product taxation and tax incentives provided to the steel sector. Third, it incorporates labor in the production function to examine its impact on CLSC outcomes in the steel industry. Fourth, it incorporates an endogenous return function into CLSC subjected to taxation. Fifth, it allows consideration of different collection channels in the steel CLSC. All of these features combined together have not been considered in the CLSC literature.

The following results based on Stackelberg equilibrium analysis are obtained:

(1) Shown analytically and numerically, output taxation creates inefficiencies in production and pricing and generates economic loss in the CLSC. However, it is also shown how tax incentives can improve the CLSC performance including profitability and consumer surplus. Governments are aware of the resulting inefficiencies, and therefore some countries such as America, Canada, and China have provided favorable tax legislation for the new products produced from a mixture of virgin and used materials.
(2) When tax incentives are not present (which is the case in less developed countries) and the product is taxed, there is still a remedy: an optimal choice of a collection channel can partially offset the inefficiencies created by taxation in the CLSCs.
(3) Consumer behavior in returning used products can also help alleviate tax inefficiencies in CLSCs. In particular, endogenous returns yield higher profitability compared to exogenous returns. This implies that the CLSC firms should target collection programs for which customers are sensitive to price and monetary incentives such as rebates and refunds provided for their returns.

The structure of the paper is as follows. Section 2 reviews a relevant literature and compares this paper to others. Section 3 presents the theoretical model, which explains productions of intermediate and final products, recycling process, and return behavior. Section 4 applies the circular economy model to the US steel industry. Section 5 provides theoretical predictions under different collection channels. Section 6 exhibits numerical results in the steel supply chain. Section 7 offers discussion of findings covering theoretical, managerial, and policy implications. The final section concludes with modeling limitations and future research directions.

2. Related literature

This section briefly reviews the closed-loop supply chain studies with regulations, and compares and contrasts this paper to the most related ones with the emphasis of price regulations. To find a subset of closed-loop supply chain studies, a keyword search suggested by a referee carried out based on the keywords "CLSC; Sustainability; Collection channel; Endogenous return; Recycling" which were attached with a search string "or". In total 5694 papers from the Web of Science Core Collection came out. A relevant subset of these papers is analyzed below to compare and contrast to this research. Note that when these keywords were attached with a search string "and", 0 paper showed up at the Web of Science.

2.1. Closed-loop supply chains and regulations

A rationale for having a circular economy is that closing the loop in supply chains provides cost advantages (Guide, 2000; Fleischmann et al., 2003; Savaskan et al., 2004) and the environmental benefits (Fliedner and Majeske, 2010; Gotschol et al., 2014; Govindan and Soleimani, 2017; Liu et al., 2021; Yunan et al., 2021). Some environmental legislations require collection of used products and recovery of materials. Therefore, collection programs have become standard in many sectors (Souza, 2013). These legislations also hold producers responsible for the environmental impact of their products after their end-of-life. Examples of such legislations include "The Waste Electrical and Electronic Equipment Directive" in Europe, "The Specified Household Appliance Recycling Law" in Japan, and "The Resource Conservation and Recovery Act" in the USA.

A branch of supply chain literature involves environmental regulations such as cap-and-trade regulations with the focus of carbon emission reductions (Xu et al., 2017, 2018), and quantity regulations with the emphasis of take-back legislations (Atasu et al., 2009; Toyasaki et al., 2011; Esenduran et al., 2017; Zhou et al., 2017; Tian et al., 2020).

2.2. Price regulations in supply chains

A growing stream of research investigates the impact of price regulations involving taxation and subsidies on supply chain (SC) outcomes. While the current paper contributes to this stream of research it is different than others in terms of modeling framework, research questions, and findings. Some related papers will be briefly discussed, followed by the contributions of this paper.

Mitra and Webster (2008) studied subsidies for remanufactured products. They assumed exogenous subsidies and found that subsidies should be provided to both manufacturer and remanufacturer. Ma et al. (2013) examined a dual channel CLSC decisions before and after subsidies and found that subsidies would increase profits for manufacturers and retailers. Hu et al. (2014) examined competition between green and traditional manufacturing firms in the presence of tax and subsidy policies. They offered guidelines to stimulate sales of green products. However, their oligopoly model neither considered a SC nor examined the effect of regulations on consumer behavior. Bian et al. (2018) considered a SC with one manufacturer-one retailer to study environmental taxation. They revealed that integrated SC is less impacted by taxation. While they focused on environmental tax and examined its impact on integrated SC, this study examines *output taxation* and reveals remedies to mitigate the negative effects of tax in CLSCs.

Hong et al. (2016) studied a reverse SC model to assess the impact of exogenous government subsidies on e-scraps. They concluded that subsidies should be provided to the processors. Chen and Hu (2018) examined equilibrium strategies under various carbon tax and subsidy scenarios. They found that dynamic carbon tax and subsidy mechanisms led firms to adopt low-carbon production technologies. He et al. (2019) characterized optimal government subsidies under different sales channels in a CLSC. They found that government and the manufacturer had divergent preferences on sales channels. Zaman and Zaccour (2020) examined the dynamics of scrappage subsidies in a Stackelberg game. They showed that the second period equilibrium subsidy was higher than the first period one. While He et al. (2019) focused on subsidy effects on sales channels, Zaman and Zaccour (2020) examined a strategic game played between government and consumers and addressed the impact of government subsidies on consumer demand.

Li et al. (2020a) examined a price competition model in which a green manufacturer competed with a non-green manufacturer. They questioned whether government would implement innovation subsidies or product subsidies? While there was no SC consideration in their model, they reported that market outcomes depended on cost and market parameters. Li et al. (2020b) assumed tax and subsidy regulations to investigate the environmental impact of product design, given a threshold greenness level. The manufacturer received subsidies if it satisfied this target. They showed that this policy did not affect wholesale price and profitability. Sana (2020) examined price competition between a green producer and a non-green producer. The green producer received higher subsidies and lower taxes and the non-green firm obtained lower subsidies and higher taxes from government. Sana characterized equilibrium outcomes, simulated model outcomes, and found that more green products would be sold in the market as long as non-green producer was taxed higher and offered no subsidies. Sana (2022a) analyzed a centralized and de-centralized two-echelon supply chain where optimal pricing, quality, and social responsibility were considered. From sustainability perspective, he emphasized the benefits of joint decision making for the supply chain firms. Mahmoudi et al. (2021) examined green and non-green omni-channel SCs. Government provided subsidies but taxed output. They showed that government interventions led firms to adopt sustainable strategies, and cooperation with third-party logistics companies boosted consumer consciousness towards the environment.

More recently, Yu et al. (2023) examined a cooperative game solution in a three-echelon CLSC subjected to a carbon tax. They showed that a grand coalition in the CLSC would lead to desired environmental and economic outcomes. Zhu et al. (2023) studied a CLSC structure to identify effective green manufacturing modes in relation to automobile production. They revealed that under a low carbon tax regime, the best mode was to implement remanufacturing. Khorshidvand et al. (2023) focused on incentive-based recycling programs and examined centralized, decentralized, and collaborative CLSC settings. They showed that the collaborative CLSC resulted in sustainable outcomes along with higher profits. Ullah (2023) examined transportation and logistics issues in a CLSC under carbon emission tax. He found a negative relation between optimal remanufacturing rate and transportation distance in the reverse supply chain.

2.3. Research gaps

While the modeling framework and objectives of this paper are different than those found in the literature, they all attempt to address the effects of government regulations on supply chain outcomes under various assumptions. However, the main novelties of this paper compared to the ones on regulations in the supply chain studies are that:

(i) It examines the *impacts of taxing intermediate products* on CLSC strategies in the steel sector.

(ii) It incorporates *labor into production function* to show its role on CLSC outcomes.

(iii) It encompasses an endogenous return function into the CLSC subjected to taxation to show how this type of consumer behavior eases some negative impacts of taxation.

(iv) It signifies the importance of using an optimal collection channel for backward activities in order to overcome inefficiencies caused by taxation in the steel CLSC.

(v) While real-world CLSC applications are very rare, this paper provides a numerical analysis using data from the US steel sector to show how the supply chain performance and steel and finished steel prices vary over various tax scenarios. The features pointed out in (i)–(v) are novel and constitute contributions to the CLSC literature. The last point (v) is especially important as De Giovanni and Ramani (2024) report that there are a few CLSC application papers using actual industry data in the literature. To be precise among the papers they reviewed only 3% of the papers uses real-world data. Table 1 presents the key modeling features, which distinguish this paper from the related papers on price regulations.

This table shows that the recent literature has put a lot of emphasis on price regulations including taxation and subsidy. While most papers in this research stream are theoretical, the recent ones offer applications mainly concerning car industry. The key reason for this could be that with the advent of electric vehicles most governments have been supporting electric vehicle makers such as Tesla, Volkswagen, Ford, and Chrysler through tax breaks and investment credits, and subsidizing customers via rebates to satisfy global and local environmental targets and spur economic activities. This is in line with their energy transition objectives which aim to reduce reliance on fossil fuel and increase the share of renewable energy generation. However, more applied studies are needed to examine the impact of price regulations in other industries. In this study, the steel industry is chosen as steel is the most recycled product and its supply chain is subject to government provided monetary incentives. Another striking feature of the recent studies is that they consider price regulations in the context of supply chains with backward activities. While such studies are rare, they are the most interesting ones as these regulations concern all CLSC stakeholders including suppliers, manufacturers, distributors, collectors, and consumers.

Table 1
Modeling features: Comparison with related literature.

Authors	Regulation	Applied	CollChannel	Labor	CLSC	EndogRet
Atasu et al.'09	Quantity	–	–	–	✓	–
Toyasaki et al.'11	Quantity	–	–	–	✓	–
Esenduran et al.'17	Quantity	–	–	✓	✓	–
Tian et al.'20	Quantity	–	✓	–	✓	–
Xu et al.'17	Environment	–	–	–	–	–
Xu et al.'18	Environment	–	–	–	–	–
GencDeGiovanni'17	–	–	–	–	✓	✓
GencDeGiovanni'18	–	–	–	–	✓	✓
MitraWebster'08	Price (S)	–	–	–	✓	–
Ma et al.'13	Price (S)	–	–	–	✓	–
Hu et al.'14	Price (T,S)	Car	–	–	–	–
Hong et al.'16	Price (S)	Laptop	–	–	✓	–
Bian et al.'18	Price (T)	–	–	–	–	–
ChenHu'18	Price (T,S)	Beer	–	–	–	–
He et al.'19	Price (S)	–	✓	–	✓	–
Li et al.'20a	Price (S)	–	–	–	–	–
Li et al.'20b	Price (T,S)	–	–	–	–	–
Sana'20	Price (T,S)	–	–	–	–	–
ZamanZaccour'20	Price (S)	Car	–	–	–	–
Mahmoudi et al.'21	Price (T,S)	–	–	–	–	–
Yu et al.'23	Price (T)	–	–	–	✓	–
Zu et al.'23	Price (T)	Car	–	–	✓	–
Khorshidvand et al.'23	–	Clothing	–	✓	✓	–
Ullah'23	Price (T)	–	✓	–	✓	–
This paper	Price (T)	Steel	✓	✓	✓	✓

✓: Yes; -: No; T: Tax; S: Subsidy. Applied: Application; CollChannel: Collection Channel; EndogRet: Endogenous return.

3. Model: CLSC structure and assumptions

Consider the following real-life situation concerning a CLSC in the steel industry. In upstream, a steel manufacturer produces steel using iron ore and scrap steel. The scrap steel comes from used vehicles which are collected by either third-party collectors or car dealers. The used car owners are incentivized by government programs such as the "Car Allowance Rebate System" of the US federal government. The program provides subsidy to used vehicle owners. When someone returns a used vehicle, he/she is offered a refund covering its scrap value and government offers a subsidy to be used for purchasing a new vehicle. In downstream, there are competitive firms which buy new steel from upstream, hire workers, and produce finished steel products such as steel sheets and rods. The labor market is also competitive, and downstream firms can hire workers at competitive wages. In this supply chain, government plays two roles: it taxes steel producers per steel output and provides subsidies to old vehicle owners. The following figures present this CSLC under two collection channels.

The model depicted in Figs. 1–2 is solved using Stackelberg equilibrium approach, which takes into account of a leader–follower type decision making process. The timing of the game is that upstream manufacturer M produces raw steel (K) from virgin iron ore and scrap steel and chooses its price (k) in the first stage. Downstream firms R decide how much raw steel (K) to buy from M, how many workers (L) to hire in labor market, and how much finished steel products (Q) to produce and sell to end-users in the second stage. At any time in the game, consumers can decide whether to dump their used items such as old vehicles to junk yards or to return them to collectors such as retailers. Government's role in this supply chain is that it exogenously chooses the amount of subsidy at the outset of the game to encourage returns, spur economic activity, and satisfy its intrinsic environmental objectives. This Stackelberg game is solved backwards, solving for downstream firms' objective function first and solving for upstream firm's objective next. This process leads to strategies which are time consistent and maximize profits in both upstream and downstream. Table 2 displays model notation before the structural details are introduced.

To tackle the research questions posed by this paper, a tractable model along with justifiable assumptions are offered. The goal is to characterize equilibrium outcomes analytically and obtain equilibrium strategies in a closed-form, which are tractable, comparable, and insightful.

Table 2
Model notation.

Notation	Description
M, R	Firms M, R
v	Quantity of returned used product
β	Recycling rate
K	Quantity of intermediate product
Q	Quantity of final product
α	Rate of production from used product
$1-\alpha$	Rate of production from raw product
c_1	Unit production cost of used product
c_2	Unit production cost of raw product
c	Weighted average cost
e	Mixture rate of intermediate products
σ	Maximum return quantity
a	Price cap
δ	Return sensitivity to price-rebate markup
f	Rebate per return
b	Consumers' price sensitivity
k	Wholesale price of intermediate product
w	Marginal cost of labor
g	Unit cost of shipping/handling
p	Retail price of final product
F	Maximum cost of collection per unit
l	M pays R per collection
t	Tax rate
n	Number of downstream firms

Collectors: Two collection channels relevant to steel industry are considered. In the first one, a third-party collector gathers used products from consumers, processes (cleaning, sorting, disassembling) and delivers them to a manufacturer. For example, when a recycling company buys an end-of-life car from an owner, it separates parts, crushes it, and then delivers pressed body to a steel company, which produces steel from virgin and used items. This collection channel is called "3rd-party direct collection". In the second one, end-users return their used products to retailers who sell them to a third-party collector, who processes and delivers them to the manufacturer. Similarly, in this

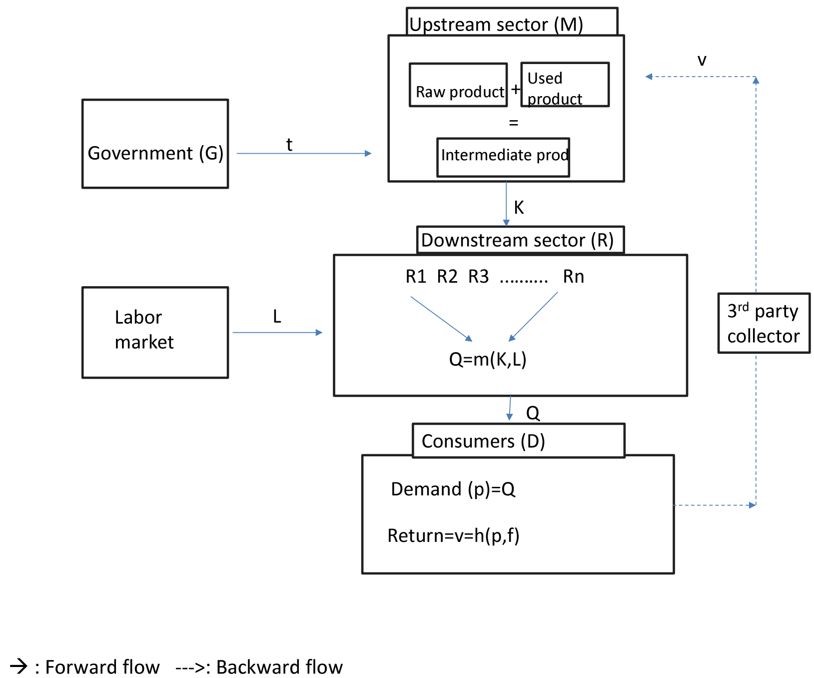

Fig. 1. The CLSC structure with 3rd party *direct* collection. M: upstream manufacturer; R: downstream firms; D: consumers; G: government.

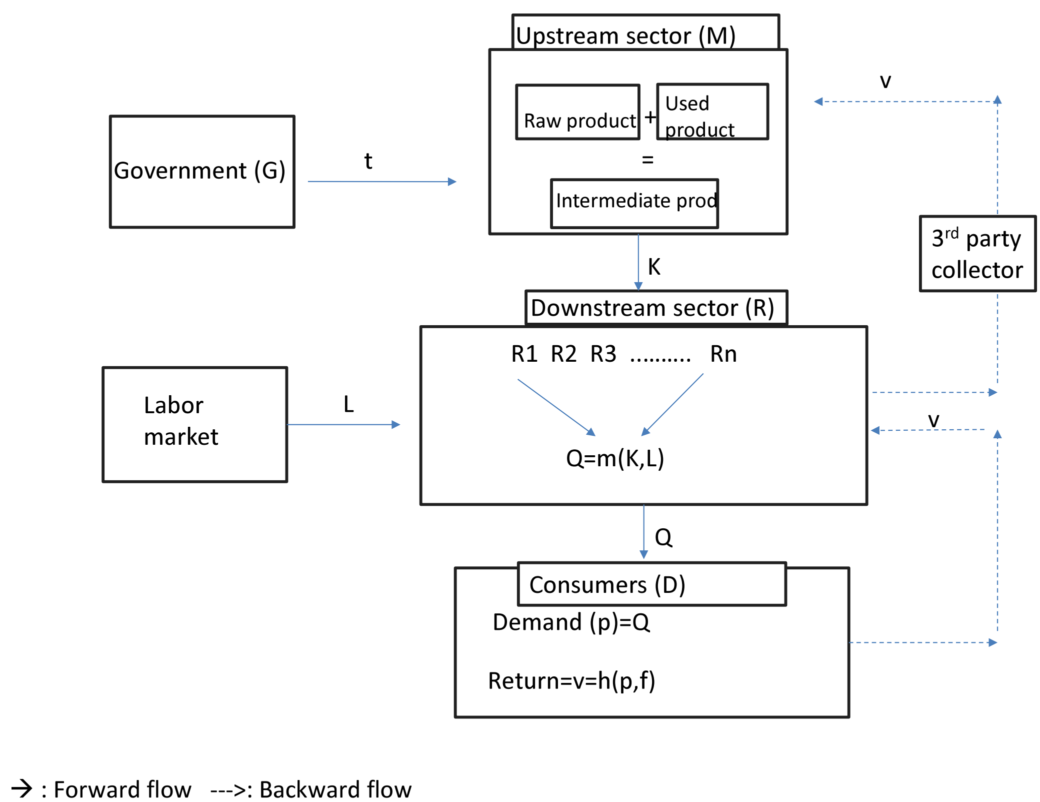

Fig. 2. The CLSC structure with 3rd party *indirect* collection. M: upstream manufacturer; R: downstream firms; D: consumers; G: government.

channel, old vehicle owners return cars to dealers who sell them to a scrap/recycling company. After processing old cars they sell them to upstream steel company. This collection channel is called "3rd-party indirect collection". The former is presented in Fig. 1 and the latter is exhibited in Fig. 2. Collection, shipping, and handling costs per return are represented by $g > 0$ in any collection scenario. These collection channels are common in the industry: while the first collection channel is popular in the UK, the second one is widespread in the US for recycling old vehicles. It will be shown that equilibrium strategies will vary over the collectors.

Recycling: The recycling function is linear:

$$m[v] = \beta v \quad (1)$$

Throughout the text, an argument of function is placed in between square brackets [.].

The amount of used product returns is represented by v, and βv denotes quantity recovered to be used for making a new product. For example, if v represents tons of scrap, only βv tones of steel is recovered, where $\beta \in (0, 1)$.

Intermediate product: Let K be the amount of intermediate good produced. $1-\alpha$ portion comes from raw material and α portion comes from recycling, where $\alpha \in (0, 1)$.

$$K = \alpha K + (1-\alpha)K \tag{2}$$

Expression (2) represents composition of intermediate product. It shows how steel is produced from virgin and scrap materials in the steel industry. α percent of a unit of steel contains scrapped material and the rest contains virgin elements. Essentially, expression (1) is the recycling function explaining how the recycled input is obtained, and expression (2) explains how virgin and recycled materials are combined to produce the intermediate product.

In Eq. (2), α is fixed regardless of the amount of collections v. That is, no matter how much scraps or used products are collected, the manufacturer cannot use all but only its α portion in making new products. This could be due to regulations (which do not allow 100% recyclables because of, say, quality issues) or chemical properties of the product (which allow amalgamation of metals at certain rates only). In the steel industry, recycled steel comes at different grades and contains different chemical elements, therefore they are processed at fixed rates or combinations. In fact, there are over 3500 different grades of steel. However, broadly speaking, steel can be categorized into four groups based on chemical compositions: carbon steel, alloy steel, stainless steel, and tool steel (see "Steel grades and properties" at https://www.thebalance.com/steel-grades-2340174).

A reason for using recycled material is that manufacturing from a scrap item usually costs less than manufacturing from a virgin material. Let $c_1 > 0$ be a unit production cost if scraps are utilized and let $c_2 > 0$ be a unit production cost if raw materials are used. In general, marginal costs are non-constant and they depend on the amount of production. In this case (as pointed out by a referee), it could happen that the unit production cost c_1 varies with the level of scraps v (and costs could increase or decrease locally). However, it is assumed constant for the sake of tractability. So the impacts of key modeling features such as endogenous return behavior, collection channel, and taxation are focused in.

Assume that $c_1 < c_2$ holds. To support this cost relation, the following figures are presented. According to the The U.S. Environmental Protection Agency (2023), there exist 79% material conservation, 95% reduction in emissions, and 97% reduction of effluents through recycling of aluminum. 90% virgin materials savings, 86% emissions reduction, 40% effluent reduction, 76% water pollution reduction, and 97% mining waste reduction were materialized through steel recycling in the US.

However, the reverse relation $c_1 > c_2$ could also hold due to high processing costs of recycling (see New York Times (2019) about recyclables sent to landfills). In any case, the relationship between c_1 and c_2 does not matter in this model because both inputs are used to make the intermediate product, and their weighted average cost is used throughout the analyses. Denote the weighted average cost c so that $c \equiv \alpha c_1 + (1-\alpha)c_2$. Consequently, the total cost of producing K units of intermediate good boils down to

$$C[K] = c_1 \alpha K + c_2(1-\alpha)K = cK. \tag{3}$$

Final product: Downstream industry is competitive. Firms (R) buy K units of intermediate product supplied by M and hire L units of labor to produce a final product. A Leontief production function is employed to produce it. This production function may suit well to industries such as metals, mining, clothing, automobile, and health care, where labor is a critical input and is combined with capital at a fixed rate. R firms use K and L amounts to produce Q units of final product:

$$Q[K, L] = min\{e_1 K, e_2 L\}. \tag{4}$$

By rescaling the coefficients, Leontief technology can be rewritten as $Q[K, L] = min\{K/e, L\}$, where $e = e_2/e_1 > 0$. This implies that $K = eQ$ units of intermediate product and $L = Q$ units of labor are combined to produce Q units of output. Let the unit price of intermediate product be k and the unit price of labor be w. In equilibrium $k > \alpha c_1 + (1-\alpha)c_2 = c$ will hold.

Demand for final product: R firms produce and sell the final product, and face a linear inverse demand:

$$p[Q] = a - bQ. \tag{5}$$

Although this demand curve is a simplistic approximation to a general demand function, Cohen et al. (2021) provide theoretical justification and Aydemir and Genc (2017) offer empirical support for the predictive power of linear demand. The application section simulates this demand function and shows that estimates of hot-rolled steel prices are near the actual prices. The demand function could be stochastic. In a recent paper, Sana (2022b) uses stochastic demand to examine a retailer's decisions in a dual-channel retail system.

The coefficients a and b are positive and represent price-cap and price sensitivity, respectively. In addition, the relation $a > ke + w > 0$ must hold, where $ke + w$ is the marginal cost of final product which is obtained by minimizing the total cost function subject to production function.

Return Behavior: The return function of used items is

$$v[p] = \sigma - \delta(p - f), \tag{6}$$

where $0 \leq \delta$. If $\delta = 0$ then the return function boils down to exogenous return and becomes $v_1[p] = \sigma$. This type of return function reflects a passive return policy or waste stream approach (Ferrer and Swaminathan, 2006). In this case, consumers voluntarily return $\sigma > 0$ amount of used products and are paid a refund f per return by a collector. The return quantity is fixed and the collector knows how much scrap is going to be processed. For example, σ could be the amount of scrap steel, or it could be the quantity of junk cars collected and processed for recycle. Alternatively, σ could refer to a recycling capacity above which additional items were not processed.

If $\delta > 0$ then the return function is endogenous and becomes $v_2[p] = \sigma - \delta(p - f)$. The end-users are paid a fixed fee/refund/rebate $f > 0$ per return and the number of returns depends on endogenous market price p of final product. $\delta > 0$ is the price sensitivity to return. This implies that consumers evaluate the difference between market price and rebate before they decide whether to keep or get rid of their old vehicles. The return quantity increases with rebates and decreases with new product prices. For example, a used car owner may evaluate resale value of their car, a rebate it receives from a dealer and/or government, and a price of new car, before he/she decides to rid of it. The expression (6) is also called an active return approach (Genc and De Giovanni, 2017, 2018).

Taxation: Assume that government implements a tax policy on CLSC operations. A likely scenario is to tax upstream manufacturer; this is because it is monopoly and adds a significant value to supply chain by producing intermediate products from used and virgin materials. Other scenarios could involve taxing downstream firms or consumers, albeit these are not interesting tax scenarios. The downstream firms are competitive and taxing them will increase their price proportionally. Taxing consumer earnings from returns is impractical and disincentivizes recycling. On the contrary, consumers have been provided subsidies to return their used items and buy new ones. Consequently, a tax policy involving taxing manufacturer's product at $\$t$ per output is adopted.

Table 3
Steel recycling rates in North America.
Source: Steel Recycling Institute (2014).

Steel recycling by sector	Rates in 2012	Rates in 2013
Steel container	71%	70%
Automotive	93%	85%
Steel Appliance	90%	82%
Structural steel	98%	97.5%
Steel reinforcement	70%	72%

Table 4
Hot-rolled steel types and prices (**$/weight**).
Source: MetalsDepot.com.

Item size and Description	Weight/Ft	Size	Price
16 GA. (.060 thick) Hot-rolled steel sheet	2.50 lb	1 × 2 Ft	$12.50
14 GA. (.075 thick) Hot-rolled steel sheet	3.13 lb	1 × 2 Ft	$13.44
12 GA. (.105 thick) Hot-rolled steel sheet	4.40 lb	1 × 2 Ft	$18.20
11 GA. (.120 thick) Hot-rolled steel sheet	5.00 lb	1 × 2 Ft	$17.00
10 GA. (.135 thick) Hot-rolled steel sheet	5.63 lb	1 × 2 Ft	$20.20

Table 5
Hot-rolled steel sheet production in the USA (**million metric tons**).
Source: Statista.com (Statista, 2023).

Year	Quantity	Year	Quantity	Year	Quantity	Year	Quantity
2000	98.93	2005	95.23	2010	75.7	2015	78.51
2001	89.76	2006	98.53	2011	83.34	2016	78.5
2002	90.72	2007	96.26	2012	87.04	2017	82.45
2003	96.14	2008	88.77	2013	86.57	2018	86.44
2004	101.68	2009	56.4	2014	89.13	2019	NA

Profit maximization problems for M and R will vary depending on collection channel. Solution paradigm is Stackelberg equilibrium because intermediate product is produced first and final product is produced next. In the steel industry, while there are a few steel producers there are many finished steel producers. Steel producers choose steel prices first, then finished steel producers buy steel and produce final products. Consequently, this sequential order of decision making renders Stackelberg framework appropriate in this CLSC.

4. Application to steel production and recycling

This section describes the actual data for steel recycling, finished steel outputs and spot prices, and calibrates model parameters (cost, demand, recycle, collection, refund) relevant to the steel sector that will be used for simulating model outcomes.

Steel is the most recycled product and automobiles are the largest source of ferrous metal in the US. For example, 11 million vehicles in 2014 and 17 millions in 2019 were recycled in the US (see The Institute of Scrap Recycling Industries at www.isri.org).

Table 3 presents steel recycling over sectors in North America. For example, recycling rate β in Eq. (1) is equal to 0.93 in 2012 and 0.85 in 2013 when recycled product is a used vehicle.

After steel is produced from recycled material and virgin iron ore in upstream, hot-rolled steel sheets are produced as final products in downstream. Hot-rolled steel sheet is examined as the final product because it is the most economical finished product for a wide variety of applications. It is easily welded, formed, and drilled. It is used in making automotive panels, tool boxes, hoppers, drip pans, fuel tanks, trailer siding, roofing, etc.

Table 4 exhibits hot-rolled steel sheet types which are sold at different dimensions including size and thickness. Spot prices in the table reflect prices on a particular day in 2023 for the smallest steel sheet with a size of 1 × 2 ft sold by the US retailer Metals Depot (metalsdepot.com, 2023). Steel sheet prices are discriminatory, nonlinear, and vary based on type (hot-rolled, cold-rolled, galvanized), thickness, weight, and size.

The total production of hot-rolled steel sheet (in million metric tons) in the US in 2000–2018 is displayed in Table 5. In addition, Fig. 2 shows the US Midwest domestic hot-rolled steel monthly futures prices, compiled from *investing.com* (Investing, 2023). Note that hot-rolled steel sheet average futures price in 2009 was $489.58 per ton when the monthly averages were converted to the yearly average.

To determine the maximum amount of used product returns, the automotive stimulus program in the US is chosen. Because it was implemented in 2009, steel production and price data in 2009 are used. The number of old vehicles returned through the program was about 690,000 (see https://en.wikipedia.org). This corresponds to $v = 690,000$ in Eq. (1). The average recycle rate is $\beta = 0.9$ (Table 3). Therefore, $\beta v = 869,400$ tons of scrap steel were processed through the stimulus program. This figure is based on the average weight of a typical car which is about 1400 kg (this comes from the average weight of the most selling cars in the world, which are Toyota Corolla, Honda Civic, Nissan Sentra, Hyundai Elantra, Volkswagen Jetta). More detailed information about car weights can be found at https://autoshopaccessories.com/how-much-does-a-car-weigh/.

The marginal cost of iron production was estimated by Crompton and Lesourd (2008) as $115.13/ton. They assumed a linear cost function similar to Eq. (3). This is a benchmark cost assumed for steel in 2009. So $c = \$115.13$ holds in (3) and it is a lower bound for the marginal production cost of steel.

Demand for hot-rolled steel sheets is estimated using price elasticity, production, and price figures in 2009. The price elasticity of demand for steel is inelastic and estimated as 0.62 by Lord and Farr (2003), which is the most recent study on price elasticity estimation for steel to the best of our knowledge. However, hot-rolled steel sheets have substitutes such as cold-rolled and galvanized steel sheets. Therefore, the actual price elasticity for hot-rolled steel sheet should be higher than 0.62. Consequently, this figure is rounded up and assumed as unit elasticity ($\epsilon = 1$). The previous studies have not reported an estimate of price elasticity for any processed steel. The price predictions (in Figs. 3–5) confirm that this is a good approximation for hot-rolled sheets.

Because inverse demand in Eq. (5) is $p = a - bQ$, demand becomes $Q = a/b - p/b$. The goal is to estimate the coefficients a and b. Elasticity information will be used to predict them. Alternatively, expression $\bar{Q} = a/b - \bar{p}/b$ could be estimated via regression if detailed data would be available, if demand was stochastic with a white noise. By definition, the price elasticity of demand equals $\epsilon = \frac{1}{b}\frac{p}{Q}$. Based on production data provided in Table 5, the actual output in 2009 was 56.4 million tons and the average steel price was $489.58 per ton which comes from data in Fig. 2. Using elasticity formula and these data points along with unit elasticity it is obtained that $b = 0.0000086$ holds. Next, using demand formula and the same price and output pair, it is obtained that $a = 979.16$ holds. Therefore, inverse demand for hot-rolled sheet in the US in 2009 is estimated as

$$p[q] = 979.16 - 0.0000086q. \tag{7}$$

Basic oxygen steel making (BOS) uses 25%–35% recycled steel (see https://en.wikipedia.org/wiki/Scrap). Therefore, the average BOS rate implies $\alpha = 0.3$ in Eq. (2). According to the US Steel Organization, 2-hour labor is needed to produce a ton of steel (see Steel.org (2008)). Because steel is an intermediate product turned into a finished steel, it is safe to assume that $e_1 = 1$ and $e_2 = 1$ hold in production function (4). This assumption is not critical because equilibrium strategies will exhibit similar characteristics with other combinations of labor and capital in Leontief technology.

Structural iron and steel workers earn the most income in New York, where they are paid about $71,000 yearly (https://www.recruiter.com/salaries/structural-iron-and-steel-workers-salary). This implies that a steel worker's average hourly wage is approximately $35, so $w = \$35/\mathbf{h}$.

To determine parameters (f, g, l), car dealership experience with old vehicle owners in the US is examined. Through the "Car Allowance

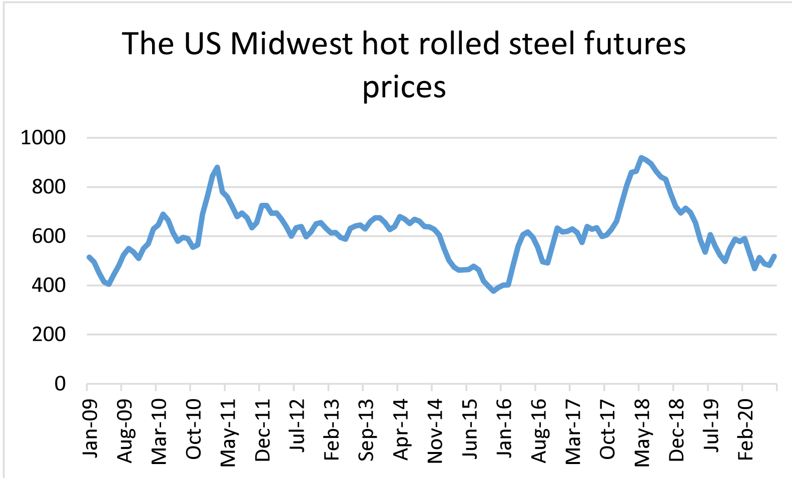

Fig. 3. The US Midwest domestic hot rolled steel monthly futures prices ($/ton).

Table 6
Parameters: The case of steel industry.

		Value
Demand:	b	0.0000086
	a	**$979.16**
	ε	1
Recycling:	α	0.30
	β	0.90
Production:	e_1	1
	e_2	1
Cost:	c	**$115.13/ton**
Wage:	w	**$35/h**
Tax rate:	t	$\{0\%, 1\%, 2\%, \dots, 19\%, 20\%\}$
Subsidy:	s	**$4500/car**
Collection:	f	**$100/car**
	g	**$50/car**
	l	**$50/car**
	σ	**690 000 cars**
Return sensitivity:	δ	$= \{low = 0.1,\ high = 0.9\}$

Note: The numbers not in bold are uniteless.

Rebate System" legislation, new car buyers were paid a scrap value for their returned cars in addition to a rebate. The car dealer-Atlantic Toyota Scion in Lynn- paid $100 to new car buyers for each trade-in. The dealer sold the old car for $150. So, the difference is $50. John Biggio, the general manager of the dealer, said that "I thought it was pretty clear that the dealers could not keep more than $50". At Gary Rome Hyundai Inc. in Holyoke, each customer was offered $50 credit towards the purchase of a new car, based on valuation of $100 per old car. Cliff Dexheimer, the general sales manager of Gary Rome Hyundai, said that "It cost more than $50 per car to transport the clunkers (i.e., old cars being scrapped) and kill them (i.e., parts removed and car body pressed), but we still gave every customer the scrap value" (Boston, 2010). Given this information, model parameter g referring to the cost of handling and shipping of old car takes $50, and parameter f representing its valuation equals $100. Also, l = $50 because the dealer received $50 per car from a recycler on top of its cost of shipping and handling. Furthermore, based on the Car Allowance Rebate System, each old vehicle owner received a fixed subsidy of $4500 from the government.

Consequently, Table 6 is formed to exhibit the parameter values that will be used for model simulations in the numerical results section.

5. Theoretical results

This section provides Stackelberg equilibrium solutions for returns, productions of intermediate and final goods, and prices in CLSC upstream and downstream sectors under taxation over different collection channels.

The choice of collection channel affects economic well-being of the CLSC stakeholders. While the optimal channel choice for backward activities has been studied under a number of assumptions, the channel choice under taxation has not been examined in the literature. Taxation will affect the channel choice because prices, inputs, outputs, and recycling quantities will change under taxation. However, remedies will be offered to alleviate the negative impacts of taxation in CLSCs in this section.

3rd-party direct collection: As depicted in Fig. 1, a 3rd-party collector directly collects used products from consumers and delivers them to the manufacturer M, who combines recycled and virgin items to produce intermediate products. M pays $\$g$ per item to the 3rd-party collector for its collection effort. This payment covers handling and shipping costs of the collector. This collection channel is mathematically equivalent to a scenario where M or its subsidiary is the collector.

Given a tax rate $t > 0$, M maximizes its profit function:

$$\max_{k} \Pi_M[.] = (k - c_1)\alpha K[k + t] + (k - c_2)(1 - \alpha)K[k + t] - v[.](g + f), \quad (8)$$

where the first two terms represent forward and backward profits associated with production of intermediate good. The final term represents the collector's revenue.

M sells each intermediate product at price $k + t$ and sends $\$t$ to government. The tax can be ad valorem (a percentage) or specific (a fixed cost). The manufacturer pays the total collection cost which is the number of returns (v) times unit collection cost ($g + f$). Note that no restriction between the number of returns (v) and the number of final outputs (Q) is imposed. This is because the used product is not converted to final product in one-to-one relation. Further, the amount of returned items at a given time may be higher or lower than the total number of outputs due to, say, inventory of recyclable items or a production lag between intermediate and final products.

Each downstream firm maximizes its profit function at a given time t

$$\max_{q_i} \Pi_R[.] = (p - (k + t)e - w)q_i. \quad (9)$$

Note that each downstream firm optimally chooses labor (L) and capital (K), which form downstream strategies. Solving the above maximization problem is equivalent to choosing labor and capital optimally, as shown in expressions (11) and (12). This is because characterizing output implicitly implies characterizing labor and capital through Leontief function. Output per firm is represented by $q_i > 0$ and quantity demanded equals quantity supplied in equilibrium: $Q = \sum_i q_i$. The marginal cost of final product equals $(k + t)e$ (unit cost of capital) plus w (unit cost of labor).

The payoff function for government (G) is

$$\Pi_G[.] = tK[k+t]. \tag{10}$$

Downstream firms' maximization problem results in $(k+t)e + w = p = a - bQ$ which leads to ordinary demands for inputs.

Demand for capital product becomes

$$K[k+t] = e(a - w - e(k+t))/b. \tag{11}$$

Demand for labor becomes

$$L[w] = (a - w - e(k+t))/b. \tag{12}$$

Both capital and labor decrease in prices k and w and tax t. Given intermediate product demand $K[k+t]$ and used product return $v[.]$, M maximizes its profit. The resulting prices (and quantities) obtained by solving expressions (8)–(9) form Stackelberg equilibrium strategies which are characterized below.

Proposition 1. *Assume that third-party direct collection takes place. Stackelberg equilibrium outcomes under taxation are as follows:*

(*i*) *Equilibrium prices and outputs with return function* $v[p] = \sigma - \delta(p - f)$ *are* $k = \frac{(a + ec - w + \delta b(f+g) - et)}{2e}$, $p = \frac{(a + ec + w + \delta b(f+g) + et)}{2}$, $Q = \frac{(a - ec - w - \delta b(f+g) - et)}{2b}$, $L = \frac{(a - ec - w - \delta b(f+g) - et)}{2b}$, *and* $K = \frac{e(a - ec - w - \delta b(f+g) - et)}{2b}$.

(*ii*) *The manufacturer's profit under endogenous return (i.e.,* $\delta > 0$*) is always higher than its profit under exogenous return (i.e.,* $\delta = 0$*):* $\Pi_{M,2} > \Pi_{M,1}$*, where subscript "2" refers to outcomes under endogenous return and subscript "1" refers to outcomes under exogenous return.*

(*iii*) *The CLSC's economic loss due to taxation defined as dead-weight-loss (DWL) is* $DWL = \frac{(a - ec - w + \delta b(f+g) + et)^2}{8b}$. *It quadratically increases in tax (t) and return sensitivity (δ).*

(*iv*) *The economic loss is higher under endogenous return than under exogenous return.*

Proofs are in Appendix.

Because the firms' objective functions are continuous, twice differentiable, and concave in prices, the first order necessary conditions along with the second order sufficiency conditions result in unique optimal prices. For a given level of upstream price, downstream firms choose their best response function optimally. Upstream manufacturer responds to downstream firms by maximizing its profit function to choose its best price. The successive best responses constitute a unique Stackelberg equilibrium outcomes as shown in the proof.

Economic implications of this proposition in the context of steel industry are as follows. Stackelberg equilibrium steel output decreases with cost of production and wages paid in downstream finished steel segment. That is, $\partial K/\partial c = -e^2/2b < 0$ and $\partial K/\partial w = -e/2b < 0$. Higher tax applied to steel manufacturers will decrease steel production: $\partial K/\partial t = -e^2/2b < 0$. Collection and recycling costs will also negatively impact steel production: $\partial K/\partial f = -e\delta/2 < 0$ and $\partial K/\partial g = -e\delta/2 < 0$. Also, higher demand for finished steel products increases demand for steel: $\partial K/\partial a = e/2b > 0$. The sensitivity analysis for quantity of finished steel with respect to the key parameters exhibits the same characteristics as those of raw steel. This is because finished steel quantity Q is just a positive multiple of raw steel output K.

On the other hand, the impact of key parameters on prices is asymmetric. Steel price sensitivity to tax $\partial k/\partial t = -1/2$ is negative while finished steel price sensitivity to tax $\partial p/\partial t = e/2 > 0$ is positive. This implies that although the manufacturer reduces its price linearly in tax to shoulder its share of tax, downstream firms must still pass the tax burden onto consumers who pay higher prices at any tax rate relative to no taxation. In the end, firms and consumers suffer from taxation, but it hurts the steel producer the most as it reduces its price and produces less output. While this happens, the steel producer uses scraps to reduce its production cost and contribute to the environment. This result holds for any return behavior because equilibrium outcomes with exogenous return mimics those with endogenous return as shown next.

When the return process is exogenous ($\delta = 0$) equilibrium outcomes satisfy $k_1 = \frac{(a + ec - w - et)}{2e}$, $p_1 = \frac{(a + ec + w + et)}{2}$, and $Q_1 = \frac{(a - ec - w - et)}{2b}$, $L_1 = \frac{(a - ec - w - et)}{2b}$, and $K_1 = \frac{e(a - ec - w - et)}{2b}$.

The supply chain's economics loss measured by dead-weight-loss (DWL) is calculated as the difference between CLSC welfare maximizing total surplus (firms' surplus plus consumers' surplus) and Stackelberg equilibrium total surplus. When $\delta = 0$, it becomes $DWL_1 = \frac{(a - ec - w + et)^2}{8b}$ which is quadratic in t. That is, economic loss increases at an increasing rate in tax. The source of DWL is taxation and M's market power because downstream firms do not cause any additional economic loss in the supply chain.

3rd-party indirect collection: In this collection channel, the end-users return their used items to sellers (R). Third-party collectors collect from R and deliver to M.

M pays \$$g$ per item to 3rd-party collectors and \$$l$ per item to sellers in downstream to cover collection, handling, and shipping costs. M maximizes the following profit function to choose its price k:

$$\Pi_M^I[.] = (k - c_1)\alpha K[k+t] + (k - c_2)(1-\alpha)K[k+t] - v[.]F. \tag{13}$$

The superscript I refers to outcome under 3rd-party indirect collection. F is the total payment per return. It includes payment to 3rd-party (g), customer rebate (f), and reward $l = F - f - g$ that R firms retain per return for accepting returns.

In downstream, there are n competitive firms and n is large. Each downstream firm i's profit function is

$$\Pi_R^I[.] = (p - (k+t)e - w)q_i + v[.](F - f - g)/n. \tag{14}$$

Here q_i is the output per firm such that $Q = \sum_i^n q_i$ holds and $v[.]/n$ is the number of collection per firm.

The maximization of (14) yields $(k+t)e + w = a - bQ$ which results in optimal demand for capital and labor: $K[k+t] = e(a - w - e(k+t))/b$, and $L[w] = (a - w - e(k+t))/b$. Given these demand functions, the manufacturer maximizes its profit in (13). Consequently, the following Stackelberg equilibrium outcomes are obtained:

Proposition 2. *Assume that 3rd-party collectors collect the used items through downstream sellers and return function is* $v[p] = \sigma - \delta(p - f)$.

(i) Stackelberg equilibrium outcomes under taxation are $k^I = \frac{(a + ec - w + \delta bF - et)}{2e}$, $p^I = \frac{(a + ec + w + \delta bF + et)}{2}$, $Q^I = \frac{(a - ec - w - \delta bF - et)}{2b}$, $L^I = \frac{(a - ec - w - \delta bF - et)}{2b}$, and $K^I = \frac{e(a - ec - w - \delta bF - et)}{2b}$, where superscript "$I$" refers to indirect collection.

(ii) The manufacturer's profit under endogenous return is higher than its profit under exogenous return: $\Pi_{M,2}^I > \Pi_{M,1}^I$.

(iii) The economic loss in CLSC is $DWL^I = \frac{(a - ec - w + \delta bF + et)^2}{8b}$. It quadratically increases in tax t and return sensitivity δ.

(iv) The economic loss under endogenous return is higher than the one under exogenous return.

Similar to the sensitivity analysis carried out for Proposition 1, Stackelberg equilibrium steel output decreases in cost and wage: $\partial K/\partial c = -e^2/2b < 0$ and $\partial K/\partial w = -e/2b < 0$. Furthermore, raw steel and finished steel productions decrease in tax: $\partial K/\partial t = -e^2/2b < 0$ and $\partial Q/\partial t = -e/2b < 0$. Consequently, the effect of taxation is that all CLSC strategies are altered. Although the manufacturer lowers its steel price to reduce the negative impact of tax on output (i.e., $\partial k/\partial t < 0$), downstream firms increase finished steel price as they have to pass the tax burden to the consumers (i.e., $\partial p/\partial t > 0$). In the end, upstream and downstream outputs decrease in tax: $\partial K/\partial t < 0$ and $\partial Q/\partial t < 0$. Therefore, taxation in CLSCs reduces consumer surplus and increases economic loss.

Corollary 1. *When returns are exogenous equilibrium outcomes under both collection channels are identical. The outcomes differ when the return function is endogenous.*

This result is obtained when outcomes in both propositions are compared. In addition, inserting $\delta = 0$ into equilibrium outcomes in both propositions directly yields the result that equilibrium outcomes are identical irrespective of the collection channel choice. Moreover, under both collection channels, the tax policy changes market outcomes in a similar manner as explained next.

5.1. The importance of collection channels under taxation

From operational perspective, it is imperative to identify the best collection channel implemented in CLSCs. This issue has not been investigated in CLSCs subjected to regulation. Moreover, this is studied here under various consumer return behaviors. The total CLSC profits under both collection channels will be compared and contrasted. There are several cases to consider:

Case A: Tax is applied to intermediate product and return function is exogenous.

When 3rd-party directly collects scraps, the total supply chain profit is equal to $\Pi_{M,1} + \Pi_{R,1} = \Pi_1$. When it indirectly collects scraps, the total profit equals $\Pi^I_{M,1} + \Pi^I_{R,1} = \Pi^I_1$. Because downstream firms are competitive, comparing the total supply chain profits boils down to comparing the manufacturer's profits over collection channels. The profits are $\Pi_{M,1} = K_1(k_1-c)-\sigma(g+f)$ and $\Pi^I_{M,1} = K^I_1(k^I_1-c)-\sigma(g+f+l)$. From Propositions 1 and 2, $K^I_1 = K_1$ and $k^I_1 = k_1$ hold. Therefore, $\Pi_{M,1} > \Pi^I_{M,1}$ holds. This implies that 3rd-party direct collection is the best option for firms when tax is applied and return function is exogenous.

Case B: Tax is not applied to intermediate product and return function is exogenous.

Insert $t = 0$ for the strategies in Propositions 1 and 2 to obtain equilibrium outcomes without taxation. Then the total supply chain profit under 3rd-party direct collection channel is $\Pi_{M,1} + \Pi_{R,1} = \Pi_1$. The total supply chain profit under the indirect collection is $\Pi^I_{M,1} + \Pi^I_{R,1} = \Pi^I_1$. Because $\Pi_{M,1} = K_1(k_1 - c) - \sigma(g + f)$ and $\Pi^I_{M,1} = K^I_1(k^I_1 - c) - \sigma(g + f + l)$, where $K^I_1 = K_1$ and $k^I_1 = k_1$, $\Pi_{M,1} > \Pi^I_{M,1}$ holds. So, again, 3rd-party direct collection channel leads to the largest supply chain profit.

Case C: Taxation is not applied to intermediate product and return function is endogenous.

In this case, $\Pi_{M,2} = K_2(k_2 - c) - (\sigma - \delta(p_2 - f))(g + f)$ and $\Pi^I_{M,2} = K^I_2(k^I_2 - c) - (\sigma - \delta(p^I_2 - f))(g + f + l)$ hold. Inserting $t = 0$ into Propositions 1–2 strategies results in $K^I_2 < K_2$ and $k^I_2 > k_2$ and $p^I_2 > p_2$. This implies that $\Pi_{M,2} > \Pi^I_{M,2}$. As a result, 3rd-party direct collection channel is preferred. Observe that this profit differential shrinks when the number of returns decreases. This will be illustrated in the following example using the industry data.

Case D: Taxation is applied in the CLSC and return function is endogenous.

Similar to Case C, the profits are $\Pi_{M,2} = K_2(k_2 - c) - (\sigma - \delta(p_2 - f))(g + f)$ and $\Pi^I_{M,2} = K^I_2(k^I_2 - c) - (\sigma - \delta(p^I_2 - f))(g + f + l)$, where $K^I_2 < K_2$ and $k^I_2 > k_2$ and $p^I_2 > p_2$. These prices imply that the total CLSC profit is larger under 3rd-party direct collection.

Consequently, based on the findings in these cases, the following result is obtained:

Proposition 3. *Given the outcomes under different return behaviors and collection channels, the followings hold in equilibrium.*

(i) If return function is exogenous, 3rd-party *direct* collection channel yields the largest CLSC profit. This holds whether tax is zero (i.e. full tax credit) or positive. In addition, equilibrium total CLSC profit decreases in the number of returns nonlinearly.

(ii) If return function is endogenous, 3rd-party *direct* collection channel yields the largest CLSC profit. This holds whether government collects tax or provides full tax relief to materials produced from recyclables. Moreover, equilibrium chain profit decreases in the number of returns nonlinearly.

The following example uses actual data from the US steel industry. The calibrated parameters in the industry are $e_1 = 1 = e_2$, $a = \$979.16$, $b = 0.0000086$, $c = \$115.13$, $w = \$35$, $f = \$100$, $g = \$50$, $l = \$50$, $\delta = 0.5$. Changing σ in the endogenous return function will show how equilibrium profit differentials change over collection channels.

Example 1. Let tax imposed on intermediate product be 10%, which corresponds to \$49 of government revenue per ton of steel production from scraps and virgin materials.

(i) Assume that $\sigma = 500$. Given the model parameters above, equilibrium outcomes are solved and profits are calculated. It is obtained that the total industry profit differential over collection channels is $\Pi_{M,2} - \Pi^I_{M,2} = \$12,771$. This implies that 3rd-party direct collection should be chosen in the CLSC.

(ii) Now assume that $\sigma = 250$. In equilibrium $\Pi_{M,2} - \Pi^I_{M,2} = \$271$ holds which implies that 3rd-party should collect directly. Observe that the total supply chain profit *nonlinearly* decreased with the number of returns.

Additional numerical results that provide further insights are offered in the following section.

6. Numerical results from the steel industry

This section quantifies the model predictions in the US steel industry. Given the calibrated data, Stackelberg equilibrium outcomes are computed and the results are simulated based on different tax rates.

It begins with assessing the impact of taxation on CLSC strategies when 3rd-party collects directly. It assumes hypothetical tax scenarios so that the tax rates vary: $t = 0\%, 1\%, 2\%, \ldots, 19\%, 20\%$. Alternatively, a tax reduction from a given rate may be considered as "tax incentive" or "tax credit" provided by governments to items which are produced using recyclables.

The tax rate of 0% implies no taxation ($t = 0$) for intermediate products. The tax scenario involving 1% tax implies \$4.9 per ton payment to government by the steel producer. This dollar amount comes from the fact that the US Midwest domestic hot-rolled steel sheet average futures price in 2009 was \$489.58 per ton (see Fig. 3). Similarly, 5% tax implies \$24.5 per ton, 10% tax corresponds to \$49 of government revenue per ton of steel production, and so on. These tax scenarios help us illustrate the impact of different tax rates (and tax credits) on the steel CLSC outcomes.

Fig. 4 depicts the impact of tax scenarios on equilibrium steel prices (k) and hot-rolled steel sheet prices (p) when return function is endogenous, return sensitivity to price is small $\delta = 0.1$, and collector collects scraps directly. In this case, the following results are obtained:

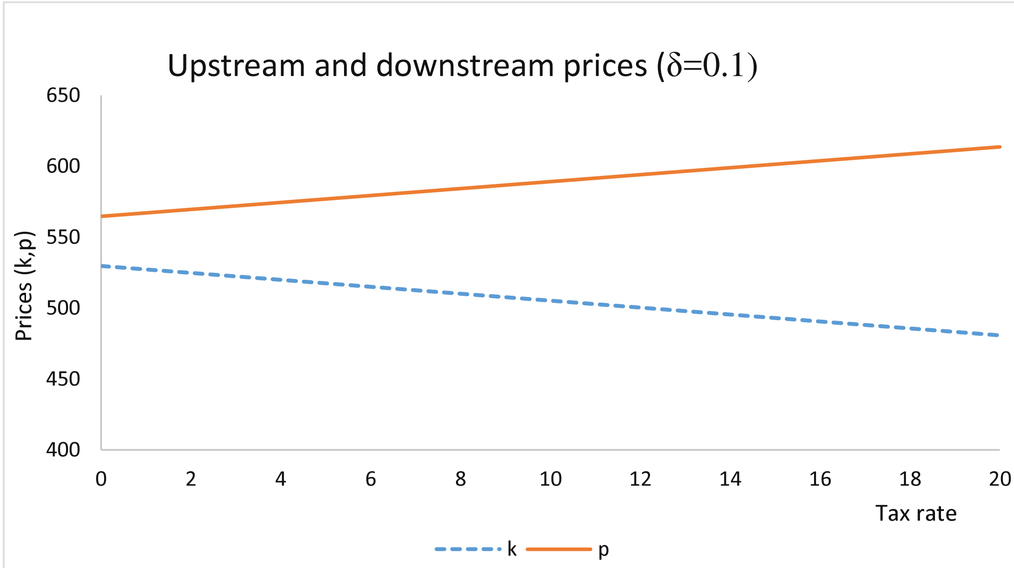

Fig. 4. The effect of taxation on steel and hot rolled steel prices ($/ton): Endogenous return (δ = 0.1); 3rd party direct collection.

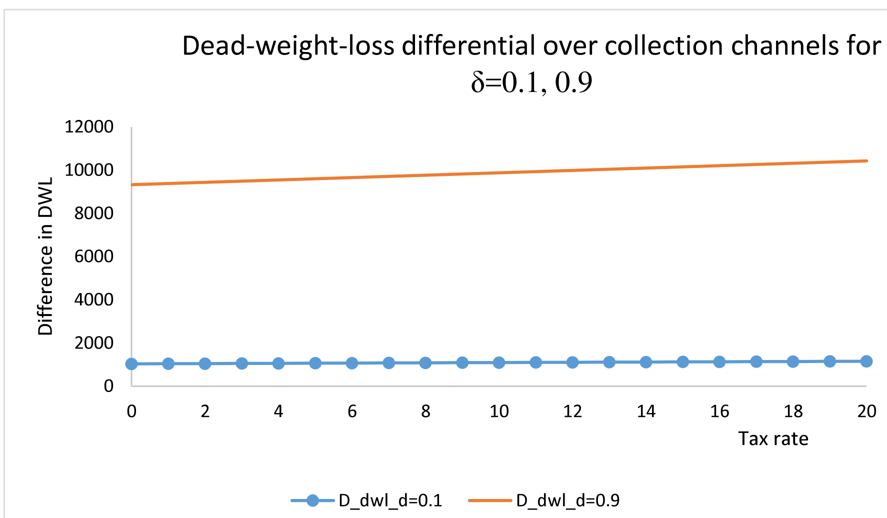

Fig. 5. Welfare loss ($) difference over collection channel with "low" and "high" return sensitivity.

(a) Steel prices linearly decrease and steel sheet prices linearly increase in tax;
(b) Because the steel manufacturer shares the principal tax burden, it decreases its price (k) to reduce loss in sales;
(c) As the tax rate increases, economic activity goes down: less labor (L) and steel (K) are combined to produce a lower quantity of steel sheets (Q);
(d) Lower steel sheet production causes higher steel sheet prices (p) in downstream, and dead-weight-loss increases with the tax rate.

Consequently, economic well-being of CLSC participants, including the end-users of finished steel, declines at the expense of tax revenues.

When return sensitivity to price is relatively high, i.e., $\delta = 0.9$, the new equilibrium outcomes are computed. It is found that under a higher return sensitivity steel and steel sheet prices go up, and outputs and the total work hours go down for any tax rate. However, the patterns of prices (and quantities) are qualitatively similar to those in Fig. 4. When steel sheet prices go up, the end-users discard and waste less. This type of end-user behavior makes upstream steel producer better off because it increases its profit through higher steel prices.

The impact of taxation on CLSC strategies when 3rd-party handles scraps *indirectly* is also assessed. It is found that the outcomes show similar characteristics to those in Fig. 4. As characterized in Proposition 2, raw steel and finished steel prices are higher when 3rd-party indirectly collects the scraps. Furthermore, as shown by simulations, price markup (finished steel price minus raw steel price) when $\delta = 0.1$ is near the mark-up when $\delta = 0.9$. This result indicates that the findings are robust to return sensitivity δ. Most importantly, as tax rate goes up, raw steel prices diverge from hot-rolled steel prices under any collection program and return sensitivity rate.

The economic loss (DWL) is also computed under each collection channel for various tax rates. Fig. 5 exhibits DWL differential (DWL under *indirect* collection minus DWL under *direct* collection) for a given return sensitivity. First, recall from Propositions 1 and 2 that taxation increases DWL. Second, the DWL differential also increases in tax, implying that indirect collection compared to direct collection results in larger economic loss at higher tax rates. Third, a higher return sensitivity to price further intensifies the economic loss under indirect collection channel. This implies that when the end-users return less scraps, indirect collection channel becomes worse than direct collection channel under taxation. According to simulation results exhibited in Fig. 5, the solid-line showing the DWL differential under a high return sensitivity ($\delta = 0.9$) is roughly nine times higher than the dashed-line showing the DWL differential under a low return sensitivity ($\delta = 0.1$). This translates into a significant economic loss and underlines the role that the return sensitivity to price in return function plays on the CLSC outcomes.

These observations along with the theoretical findings in Propositions 1–3 lead to the following main result of this paper:

Theorem 1. *The negative impacts of taxation including loss in economic activity can be alleviated by consumer return behavior and/or collection channel choices in CLSCs.*

7. Discussion of findings

This section discusses the novelties and key findings of this research and categorizes them into theoretical, practical, and policy implications relevant to sectors which are architecturally designed as CLSCs. While this paper focuses on the steel industry, it may be adopted to other industries such as energy, telecommunications, computer hardware, mining, automobile, and metals in which there is significant backward activities wherein scraps and recyclables are used in producing new products. Therefore, this research provides significant implications in doubling down environmentally sustainable circular economies.

7.1. Theoretical implications

Based on the theoretical analyses, it is first shown in the presence of taxation that equilibrium CLSC outcomes change over collection channels and return behavior. Specifically, when return function is exogenous ($\delta = 0$, so $v_1[.] = \sigma$), equilibrium outcomes under 3rd-party *direct* collection will be identical to the ones under 3rd-party *indirect* collection. However, when return function is endogenous ($\delta > 0$, so $v_2[.] = \sigma - \delta(p - f)$), the results differ. In particular, equilibrium prices are always higher under indirect collection programs. In Proposition 1, the payment $(f + g)$ relevant to backward activities shows up in all strategies under direct collection. In Proposition 2, the payment F appears in all strategies under indirect collection. The difference $F - (f + g)$ is the reward per collection for downstream firms. Because this payment is positive, $F - (f + g) > 0$, all intermediate and final product prices are strictly higher under 3rd-party indirect collection channel. The total chain profits over collection channels also differ because of different prices obtained under different collection schemes. In addition, for a given collection channel, the manufacturer's profit and the total supply chain profit are always higher under endogenous return.

Second, the economic loss (measured by dead-weight-loss) is higher under indirect collection. Therefore, CLSC firms and consumers are always better off when 3rd-party directly collects the returns.

Third, whether direct or indirect collection channel is implemented higher tax always augments economic loss at an increasing rate. That is, dead-weight-loss quadratically increases in tax because $\partial^2 DWL^I/\partial t^2 > 0$ and $\partial^2 DWL/\partial t^2 > 0$ hold. In addition, taxation results in a lower price and output for the manufacturer and a higher final product price for consumers. Therefore, higher tax rates contribute to larger economic loss. This in turn implies that tax reductions or credits will bring about immense economic benefits for CLSCs.

Fourth, consumer return behavior affects the magnitude of economic loss. On one hand, the total CLSC profit is higher under endogenous return behavior. On the other hand, the aggregate loss to the CLSC participants is lower under exogenous return behavior. So, return behavior implies a trade-off between profitability and the total surplus. However, endogenous returns can stimulate returns, improve recycling activity, and provide substantial environmental benefits. As a result, these effects imply that return behavior is a key tool to be considered in designing sustainable and efficient CLSC networks.

Fifth, regardless of which collection channel is chosen, the marginal impact of tax on any equilibrium strategy is the same. Specifically, under endogenous returns, the marginal impact of tax on intermediate product price is $\partial k_2/\partial t = 1/2$ when direct collection channel takes place, and it is $\partial k_2^I/\partial t = 1/2$ when 3rd-party collects indirectly. For all other equilibrium strategies, the rate of change of a strategy with respect to a change in tax will also be identical across the collection channels.

Consequently, taxation alters all equilibrium outcomes and reduces economic activity in CLSCs. However, there are remedies available for managers and policy makers. As Theorem 1 suggests "The negative impacts of taxation including loss in economic activity can be alleviated by consumer return behavior and/or collection channel choice in CLSCs".

7.2. Managerial implications

This research offers several practical managerial implications that CLSC firms should apply to their businesses to improve profitability.

(i) CLSC firms in the steel industry should always choose 3rd-party direct collection channel. This is the most profitable operational choice in collecting scrap steel. This result holds true whether tax rate is small or large. This finding is robust to the return behavior, whether it is exogenous or endogenous. Even if the number of returns were small, 3rd-parties still should directly collect the cores and/or scraps.

The literature does not offer unanimous answer for the choice of optimal collection channel. For example, Savaskan et al. (2004) find that the retailer should collect the used products, while De Giovanni (2014) reveals that the manufacturer should handle them. While these studies are theoretical, they neither consider price regulations nor take endogenous return behavior into account. Because this research examines a specific industry, one can at least say what the optimal collection channel should be in the steel sector.

A managerial intuition for this result is that when returns are exogenous, end-users are not able to impact CLSC strategies. Stackelberg equilibrium strategies are identical irrespective of the choice of collection channel. In addition, because manufacturers use returns in manufacturing, production costs go down. Therefore, the total chain profit is higher when 3rd-party collects directly. However, the impact of endogenous return behavior is less trivial. When end-users are able to impact CLSC strategies through their returns, profit-maximizing prices change over collection channels. This adds complexity to compare the total chain profits across the collectors. However, if prices and outputs can be ranked, as is the case in this CSLC, then the total chain profits over collection channels can be easily compared. Based on equilibrium outcomes, it is obtained that the total CLSC profit is larger under direct collection.

(ii) Under taxation supply chain managers should target collection programs for which end-users endogenously respond and determine their return decisions. This can counteract the negative impacts of taxation. However, while this is a profitable strategy for firms, it has limitations.

This result is obtained for the steel CLSC. Genc and De Giovanni (2017) found a similar result in a theoretical CLSC without tax considerations. Therefore, the impact of endogenous return on outcomes seems to be robust to different CLSC settings.

When returns are recycled and parts are utilized to make new products, production costs go down, natural resources are saved, and pollution is reduced. For example, recycling an old vehicle for steel reduces CO2 emissions by 58 percent, saves 2500 lbs. of iron ore, and decreases electricity consumption by 60 percent compared to production from virgin materials (see https://www.isri.org/recycled-commodities/ferrous). Recycling of aluminum provides 79% material conservation, 95% reduction in emissions, and 97% reduction of effluents (see http://www.canaryinstitute.ca/publications/Scrap_Mining.pdf).

However, some municipalities in the US downsized or terminated their recycling programs and recyclables such as glass, newspaper, tin, and plastic were sent to landfills due to their abundance and higher recycling costs (see https://www.nytimes.com/2019/03/16/business/local-recycling-costs.html). This is a case in which too many recyclables may cost a lot to the environment.

Consequently, as shown in this paper, endogenous returns provide numerous benefits to firms, consumers, and the environment. However, there are limits of those aforementioned benefits. Monetary incentives such as refunds and subsidies offered to consumers for their end-of-life or used products may lead to unintended economic and environmental consequences which could be in the form of over consumption of new products and oversupply of used products.

7.3. Policy implications

This paper is in line with the recent government policies which have been expanding tax credits to combat climate change and spur economic activities in the era of energy transition. For example, "The Inflation Reduction Act" of the US signed into law in 2022 has provided monetary incentives in the form of green tax credits for firms to invest in cleaner production technologies (https://www.whitehouse.gov/cleanenergy/inflation-reduction-act-guidebook/). On April 20, 2023, the Canadian government has announced that it will provide $13 billion in tax credits and subsidies to Volkswagen for production of electric vehicle batteries (https://www.reuters.com/business/autos-transportation/canada-offering-more-than-c13-bln-over-decade-volkswagen-battery-plant-govt-2023-04-20/).

In addition to providing remedies to improve efficiency and profitability in CLSCs, this research has environmental implications. Using less of new material and more of recyclables will bring about immense pollution reduction, energy saving, and natural resource preservation. Therefore, this paper recommends policy makers to provide tax incentives for the new products produced using scraps and recyclables.

Furthermore, as shown in the propositions, taxation of intermediate output produced from scraps alters all supply chain strategies and decisions including production, hiring, pricing, and returns. This result holds for any consumer return function and any collection channel in the steel CLSC. Most importantly, while end-users are not taxed directly, they are disincentivised for returning their used items as returns go down with tax rate hikes. Because taxation is a burden for all CLSC stakeholders, tax incentives provided by governments will therefore improve firm profitability and consumer surplus.

The findings of this paper can be supported by real-life evidence. For example, China has already implemented new tax policies for new goods produced from scraps. To promote its circular economy, China's State Administration of Taxation and Ministry of Finance have granted recycling companies favorable value-added tax (VAT) through the legislation "Circular on Adjustments of VAT Treatment to Products and Services Output through Comprehensive Utilization of Resources (Caishui [2011] No. 115)". This policy has been applied to a number of recyclables including metals, paper, fabric, waste plastic/rubber oils, petroleum coke, carbon black, pulp, aluminum powder, automobiles, motorcycles, household electrical appliances, pipes, chemical fibers as well as glass and plastic bottles (https://www.china-briefing.com).

Other countries have issued similar policies. For example, Scharf (1999) examined the impact of Canadian tax system on the marginal cost of final goods produced from virgin and recycled materials. Scharf found that while Canadian tax system favors the use of virgin materials in metal and glass production, it provides better tax incentives to companies which use recycled material in making plastic products.

In the US, according to the Environmental Protecting Agency's report entitled "Tax Credits: An Incentive for Recycling?" (Sparks, 1998), about half of the states have implemented tax credits for recycling. However, Sparks noted that the direction of tax credit programs is uncertain as it is costly to monitor and implement. John Savage, the administrator of the Oregon Office of Energy (Salem) said that "The success of recycling hinges on using recycled materials as ingredients in the manufacture of new products". This opens up the question of what proportion of recycled material should be used in making final products to warrant tax credits? While this is an open-ended question, the proportions vary from product to product and policy makers have already chosen random threshold levels which are revisited and updated over time. However, whatever portion of recycled material is utilized to make new products or whichever product is deemed to qualify for a tax incentive, recycling generally provides immense economic and environmental benefits.

8. Concluding remarks

This paper examines the implications of taxation in a steel CLSC where return function is endogenous, tax is implemented on intermediate products which are produced from combinations of virgin and used products, and there is a competitive downstream industry in which firms buy intermediate products, hire workers, and produce final products via Leontief technology. The paper shows how tax alters CLSC strategies and decisions by characterizing Stackelberg equilibrium outcomes. It calibrates model parameters to quantify the economic cost of taxation using actual data from the US steel industry. Specifically, it demonstrates how raw steel and hot-rolled steel prices change with respect to tax, collection channel, and return sensitivity. The takeaway message of this paper is that collection channel and consumer return behavior are the key tools to be utilized in order to mitigate tax burdens on the CLSC firms.

In comparison with the past work, the true benefits of this study are that (*i*) its methodology is realistic, tractable, and describes CLSC in the steel industry; (*ii*) it is detailed and clearly specifies recycling process and production functions for manufacturing intermediate and final products in the steel industry; (*iii*) it integrates endogenous return function into steel supply chain to describe scrap steel return behavior; (*iv*) it incorporates labor into production function, which has been omitted in CLSC studies, to examine its impact on CLSC outcomes in the steel industry. Compared to related work in the literature, these modeling features are unique and may help investigate CLSCs in other industries to reveal economic and environmental benefits of tax reductions and incentives.

This research suggests that governments should reduce tax rates applied to products manufactured from scraps and recyclables. Although it theoretically and empirically shows the benefits of tax reductions in the steel industry, the methodology offered in this paper can be applied to related industries such as metals, energy, and automobile. A real-life implementation of the tax credits is that China's new tax law has specified a group of recyclable products that benefit from reduced tax rates. Nevertheless, if tax incentives are not provided by governments, this paper offers solutions to improve consumer surplus and firm profitability and reduce loss in economic activity in CLSCs. First, firms can choose a profit enhancing collection channel to lower the negative impacts of taxation and improve CLSC profits. Second, in order to increase profits firms can initiate collection programs targeting products for which consumers exhibit endogenous return behavior.

The paper has limitations and could be extended in several directions. First, demand and cost functions are deterministic and approximated to be linear. Although stochastic elements may complicate the model, numerical approximation methods may be used to obtain expected strategies along with a broader range of prices and outputs.

This could facilitate a better assessment of the impact of tax reductions on profitability and the environment. Second, the model assumes exogenous tax. While this is true in some industries, governments could optimize it to minimize the total system costs. This could be easily adopted in the current setting of the model. By characterizing optimal tax rate, one could find out its exact impact on the CLSC outcomes. Third, it is assumed that downstream firms produce and sell the final product. A more realistic situation would involve a three-echelon supply chain, separating these operations by adding a midstream. While this complicates the model solution, it will provide different quantitative predictions. Fourth, a technology other than Leontief may be assumed; an alternative is Cobb–Douglas which provides flexibility in input choices. However, it is an empirical question which production technology is to be employed for a given sector? That is, by only changing production technology, the proposed model may be used to study other industries. Fifth, solving for a centralized integrated solution as a benchmark to see how the results could differ from a decentralized solution would also be viable. The results will not change either qualitatively or quantitatively as long as production technology is Leontief. However, the results will likely change under a different technology. In this case, policy makers could be interested in finding the centralized solution to set their environmental targets. Sixth, one may assume sophisticated rebate mechanisms which may involve consideration of quality and size of returns, which can affect equilibrium solutions. This could be a more realistic setting and the model results would likely change for products other than steel. Finally, this paper theoretically predicts that tax reductions or credits bring about immense economic benefits for CLSCs in the steel industry. It could be interesting to quantify the economic benefits in other industries from the social welfare point of view. This could help estimating the impact of tax incentives provided to CLSCs on gross domestic product (GDP).

CRediT authorship contribution statement

Talat S. Genc: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing.

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.

Data availability

The paper does not use a specific or private data. All representative data used in the paper is publicly available and their sources are defined in the paper.

Appendix

Proof of Proposition 1.

(i) M maximizes

$$\Pi_{M,2}[.] = (k_2 - c_1)\alpha K_2[k+t] + (k_2 - c_2)(1-\alpha)K_2[k+t] + \\ (\quad -\sigma + \delta((k_2+t)e + w - f))(f+g),$$

where $K_2[k+t] = e(a - w - e(k_2+t))/b$ because profit maximization problem of downstream firms leads to $(k_2+t)e + w = p = a - bQ$ and $K_2 = eQ_2$. Note that this profit function is twice differentiable and strictly concave in price. Therefore, it attains a maximum so that the first order condition $d\Pi/dk = 0$ and the second-order condition $d^2\Pi/dk^2 = -2e^2/b < 0$ hold. The first order condition for M's profit with respect to its price k results in

$$k_2^t = \frac{(a + ec - w + \delta b(f+g) - et)}{2e}.$$

The final product price and outputs will immediately follow from this intermediate product pricing. This upstream price k is unique (because of strict concavity of the objective function) and forms equilibrium since it constitutes best response to downstream followers' best response function (see Amir, 1996; Genc et al., 2007). These successive best responses, therefore, constitute Stackelberg equilibrium. Because prices are part of equilibrium, quantities in the Proposition which directly follow from prices are part of equilibrium too.

(ii) Inserting the optimal prices and quantities into the profit functions under each return behavior and taking the difference lead to

$$\Pi_{M,2} - \Pi_{M,1} = (K_1 - \frac{e\delta(f+g)}{2e})(k_1 - c + \frac{\delta b(f+g)}{2e}) - K_1(k_1 - c) \\ + \sigma(f+g) - (\sigma - \delta(\frac{a + ec + w + \delta b(f+g) + et}{2} - f))(f+g),$$

which further reduces to $\Pi_{M,2} - \Pi_{M,1} = \delta(f+g)(p_1 - f + \delta b(f+g)/4)$, which must be positive because price of new product p_1 must be greater than the rebate f for the used product. In terms of model parameters this profit difference is equal to $\delta(f+g)(a+ec+w+et-2f+\delta b(f+g)/2)/2$.

(iii) Only M's supply chain power causes economic loss (DWL) as downstream firms cannot influence the final product price. In this case, $DWL = (p - p_c)(Q_c - Q)/2$, where (p_c, Q_c) is the competitive price and quantity pair. Specifically, $Q_c = (a - ce - w)/b$ and $p_c = ce + w$. The equilibrium price and quantity derived in part (i) are $p = (a + ec + w + et + \delta b(f+g))/2$ and $Q = (a - ec - w - et - \delta b(f+g))/2b$. Inserting these price and quantity expressions into the DWL equation, $DWL = (a - ec - w + et + \delta b(f+g))^2/8b$, which is strictly positive. Because the coefficients of t and δ are positive, $\partial DWL/\partial t > 0$ and $\partial DWL/\partial \delta > 0$ must hold.

(iv) When $\delta = 0$, DWL becomes $DWL_{\delta=0} = (a - ec - w + et)^2/8b$ which is clearly less than $DWL_{\delta>0}$ because $\delta > 0$. □

Proof of Proposition 2.

(i) When 3rd-party collects indirectly, M maximizes

$$\Pi_M^I[.] = (k - c_1)\alpha K[k+t] + (k - c_2)(1-\alpha)K[k+t] \\ - \sigma F + \delta((k+t)e + w - f)F,$$

where $K[k+t] = e(a - w - e(k+t))/b$ because downstream firms are price takers, implying marginal cost equals price $(k+t)e + w = p = a - bQ$ and $K[.] = eQ[.]$ and $L[.] = Q[.]$ holds because of the Leontief production. Because M's profit function is twice differentiable and strictly concave in price, it attains a maximum so that $d\Pi/dk = 0$ and $d^2\Pi/dk^2 < 0$ hold. The first order condition for M's profit function leads to the optimal price

$$k^I = \frac{(a + ec - w + \delta bF - et)}{2e}.$$

The optimal final product price p and output Q and inputs K and L immediately follow from this optimal intermediate product price k. This upstream price k is unique and forms Stackelberg equilibrium since it constitutes best response to downstream followers' best response function p. These successive best responses constitute Stackelberg equilibrium.

(ii) Similar to the third part of Proposition 1, $\Pi_{M,2}^I - \Pi_{M,1}^I > 0$ will also hold because $p_1^I > f$.

(iii) As before, $DWL^I = (p - p_c)(Q_c - Q)/2$ holds, where (p_c, Q_c) is the competitive price and quantity pair. Specifically, $Q_c = (a - ce - w)/b$ and $p_c = ce + w$. The equilibrium price and quantity derived in part (i) are $p = (a + ec + w + et + \delta bF)/2$ and $Q = (a - ec - w - et - \delta bF)/2b$. Inserting these price and quantity expressions into the DWL equation, $DWL^I = (a - ec - w + et + \delta bF)^2/8b$ is obtained which is strictly positive. Also, because the coefficients of t and δ are positive, $\partial DWL^I/\partial t > 0$ and $\partial DWL^I/\partial \delta > 0$ must hold.

(iv) When $\delta = 0$, the DWL becomes $DWL_{\delta=0}^I = (a - ec - w + et)^2/8b$ which is clearly less than $DWL_{\delta>0}^I$ as derived above. □

Proof of Proposition 3. This result will be proved in the setting of the proposed CLSC model. From Propositions 1 and 2 $DWL^I > DWL$ is obtained, which holds for any δ and other model parameters. It is also obtained that $\partial DWL^I/\partial\delta > 0$ and $\partial DWL/\partial\delta > 0$. Denote $D = DWL^I - DWL$. After several algebraic simplifications, obtain $D = [(\delta bl)(2\delta b(f+g)+\delta bl)+2(a-ec-w+et)(\delta bl)]/8b$. All terms in the parentheses are positive and the coefficient of δ is positive. Therefore, $\partial D/\partial\delta > 0$ holds. □

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