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Modeling oligopsony market for end-of-life vehicle recycling

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ABSTRACT

End-of-life vehicle (ELV) recycling markets in emerging economies are characterized by the existence of plenty of informal dismantlers and a few formal dismantlers. The nature of these markets can be characterized as oligopsony markets, where few buyers (dismantlers) compete to purchase ELVs from a large number of sellers (ELV owners). High initial investment creates a barrier to entry and exit for formal dismantlers, whereas the perfectly competitive nature of the informal dismantling market enables free entry and exit of informal dismantlers. In this paper, we consider a market with one formal dismantler and few homogeneous informal dismantlers, and the dismantlers compete by offering a higher price for ELVs. We develop a system dynamics model to capture the feedback effects of competition in the ELV recycling market where the increase in the price of ELV reduces the profitability of dismantlers, which affects the future price increase of ELV and leads to the exit of informal dismantlers. This, in turn, creates fluctuations in dismantling quantities and scrap supplies leading to fluctuations in scrap prices. Using Indian data, the simulation results show that the competition leads to the higher market price for ELV, but a lower profit for dismantlers and reduced aggregate dismantling capacity due to the exit of informal dismantlers. The market price of ELV will rise by more than 200% in 10 years, whereas the existing informal dismantling capacity reduces to less than 50% during the same period. The higher capacities of the formal dismantler lead to the rapid exit of informal dismantlers thereby diminishing the effects of competition resulting in the lower market price for ELV. From our analysis, we recommend that establishing formal dismantling units with high capacities and vertical integration of vehicle manufacturers and end-of-life management systems aligned with suitable policy instruments will ensure more environmentally sound recycling.

1. Introduction

The global vehicle population is ever-increasing and has reached about 1.4 billion in the year 2018 (Chesterton, 2018). The increasing sale of vehicles also leads to an increase in the replacement of obsolete vehicles called *end-of-life vehicles* (ELVs). It is estimated that about 21.8 million ELVs will be generated in the year 2020 (Li et al., 2020). As vehicles are composed of many materials such as metals, non-metals, plastic, and glass. ELVs are a good secondary source of materials when they are recovered efficiently. The end-of-life management systems aim to increase the economic and environmental benefits of the recovery. The efficient recovery from material abundant ELVs provides an alternate source of materials during global supply chain disruptions and may enable the development of a circular economy.

Globally, ELV management systems can be classified as *formal* or *regulated* systems and *informal* or *unregulated* systems (In this paper, we use the term 'regulated ELV management systems' for those markets where the ELV management systems are governed by either legislations specific for ELV management or any other environmental legislations concerning ELV management and 'unregulated systems' for those with the absence of the above legislations.). In regulated systems, legislations are laid based on extended producer responsibility (EPR) where the manufacturer of the vehicle has to bear the cost of recycling and recovery (if any) at the end-of-life. Mohan and Amit (2020) provide a detailed description of the material and financial flows in an ELV management system. The flow of the ELV management system starts with the last owner of the ELV. The ELVs are collected by dismantlers who dismantle an ELV into the different components. The components may be sent for the appropriate product recovery activities, or sold

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in the secondary market, or scrapped, or disposed of. The remaining of the ELV called *hulk* is sent to a shredder, where the hulk is crushed and ground, and the various scrap is separated through physical and chemical means. The scrap is sold in the scrap market. The remaining of the ELV called as the automotive shredder residue (ASR) comprises of non-recyclable materials that are either sent for landfill or energy recovery. The scrap is used for recycling materials that are used for making vehicle components thereby closing the chain of material flow. In some regulated systems, a recycling fee is present that may be borne by the vehicle manufacturer or the first owner and is managed by a fund management system.

While the regulated ELV systems are present in developed economies such as EU and Japan, unregulated ELV systems are present in emerging economies such as India and China. Contrary to the EU and Japan, where the cost of dismantling and recycling of an ELV exceeds the benefits, ELV is traded as a valuable resource in emerging economies (Hu and Wen, 2015). The absence of regulations in the ELV management system in emerging economies leads to the growth of informal dismantlers. The informal dismantlers try to maximize their revenue from an ELV and shredders are absent in many unregulated ELV management systems. The informal dismantlers follow poor technological and occupational practices in the ELV dismantling process and dispose of the waste from ELV dismantling in an uncontrolled way. This creates environmental and occupational challenges leading to a reduction in the overall efficiency of ELV dismantling such as the case of the Indian ELV dismantling system (Sharma and Pandey, 2020). The informal dismantling used to generate their major revenue through the sale of vehicle parts, but the decreasing scope of used parts sale and fluctuating scrap prices have reduced their profitability (Akolkar et al., 2015). The scrap is traded as a commodity and the fluctuating scrap prices affect the profitability of the informal dismantlers. This makes the informal ELV dismantling system close to a perfectly competitive market. The informal dismantlers may conduct dismantling only when they are profitable and refrain from dismantling when not profitable and may engage in other business (Akolkar et al., 2015). Mohan and Amit (2020) termed this entry and exit of dismantlers from the market as *dismantlers' dilemma*. They find that the *dismantlers' dilemma* constraints the dismantling capacity and thereby the scrap supply in informal ELV recycling markets. Thus, the growth in informal recycling markets is restricted.

The ELV recycling system is a closed-loop supply chain involving various processes of multiple agents. ELV recycling literature considers various operational and supply chain issues such as: production planning in ELV recycling factories (Qu and Williams, 2008; Simic and Dimitrijevic, 2012; Williams et al., 2006), developing reverse logistic network for ELV recycling (Cruz-Rivera and Ertel, 2009; Vidovic et al., 2011), and ELV allocation to recycling factories (Simic, 2016a; 2016b) and strategic planning problems for ELV recycling (Simic, 2015; Simic and Dimitrijevic, 2013). This literature focuses on optimizing the payoffs of individual agents in the ELV supply chain neglecting the interaction between agents. In the absence of coordination, the agents try to maximize their surplus leading to sub-optimal performance of the system. The agents are interdependent as the individual agent's decision on increasing their profitability will influence other members' decisions that in turn affect the entire system. The inter-dependency among agents leads to the generation of feedback loops that play a pivotal role in deciding the governing behavior of the system. While for formal ELV management systems, the environmental and market regulations increase the system complexity, in unregulated systems the commodity nature of the scrap market and market imperfections increase the system complexity. This necessitates the importance of complex system analysis of ELV management systems and system dynamics (SD) modeling is a suitable approach. SD models have been developed to analyze the dynamics of ELV systems (Karagoz et al., 2019). The literature of SD analysis of ELV systems deals with the complex nature of formal and informal systems.

The SD literature on formal systems covers various aspects that give implications for policymaking. Zamudio-Ramirez (1996) and Bandivadekar et al. (2004) consider the impact of change in vehicle material composition on the profitability of ELV dismantling and recycling industry in North America. Zamudio-Ramirez (1996) identifies that material substitution reduces the profitability of ELV management systems and may lead to reduced benefits to the existing market-based systems. Bandivadekar et al. (2004) identify the need for dismantlers to increase the dismantling rate for better profitability. Amaral et al. (2006) analyze the Portuguese recycling industry and proposes to implement improved design for recycling and greater dismantling and component recovery over implementing ASR technology to attain the recycling targets. Inghels et al. (2016) analyze the ELV recycling system of passenger cars in Belgium. Considering various scenarios of macroeconomic and technological factors they conclude that Belgium can reach EU ELV regulation targets and they also suggest possible strategies to maintain the targets. Kumar and Yamaoka (2007) use system dynamics modeling in the context of the Japanese car recycling sector. They propose policy measures such as imposing a tax to prevent the export of used cars from Japan to facilitate a closed-loop ecosystem of car recycling and manufacturing in Japan. El Halabi and Doolan (2013) develop causal loops to understand the various factors affecting the dynamics of ELV sourcing, workforce, and land development in the context of ELV recycling in Australia. They propose various scenarios for the model-building to generate policy insights in the Australian context.

SD Models analyze the economics of various business models related to ELV recycling. Hedayati (2016) with the help of an SD model conducts a sustainability assessment to assess the best business model for energy recovery from ASR in the Australian ELV recycling context. Rosa and Terzi (2018) extend the model of Zamudio-Ramirez (1996) to include the additional recovery of automotive electronic components other than scrap recovery and find that to be economically beneficial to the dismantlers and shredders. Farel et al. (2013) develop an SD model that recommends a nationwide network for effective ELV glazing recycling in France.

SD models also analyze the ELV recycling systems of emerging economies. Azmi and Tokai (2017) estimate the ELV generation in Malaysia until the year 2040 using SD modeling. They identify an increase in ELV generation in various scenarios such as lower vehicle tax, the possible change in vehicle emission standards, and penetration of more electric vehicles and hybrid vehicles into the vehicle stock for ELV estimation. Chen et al. (2015) evaluate the impact of various government policies such as government subsidies, value-added tax, deposit-refund systems, and a combination of deposit systems & subsidies on ELV recycling in China and recommend initial subsidies and thereafter a shift to deposit systems by 2030 for better ELV recycling. Wang et al. (2014) consider the impact of various subsidy policies such as initial subsidy, recycling subsidy, R & D subsidy, and production subsidy on remanufacturing and recycling industry in China. On analyzing the impact of the implementation of subsides individually or as a combination, they identify that the combination of subsidies prove to be effective even if they are costlier. Mohamad-Ali et al. (2018) develop causal loop diagrams to understand the factors that improve the effectiveness of ELV recycling and the aftermarket industry in Malaysia. They characterize the causal relationships in the existing system and identify the influence of the Malaysian government's aftermarket policy on them.

Mohan and Amit (2020) is the first to model the dynamics of informal ELV recycling systems using system dynamics. They analyze the informal ELV recycling system in India and identify that the *dismantlers' dilemma* deters the growth of ELV dismantling in India. They recommend vertical integration of dismantlers and raw material suppliers and government support for the sustainability of ELV recycling in India. The rapid increase in the sale of new vehicles, decrease in life-cycle of vehicles, and regulatory measures such as replacement of vehicles to new emission norms have paved the way for an increase in the generation of ELVs in emerging economies. The increasing commodity prices and opportunities for product recovery have led to the entry of formal dismantlers in ELV recycling markets of emerging economies. For example, a formal dismantler "Cero Recycling" has commenced its dismantling operations in India in 2018 (cerorecycling.com, 2020).

The presence of formal and informal ELV dismantlers in a market will lead to competition between them. The dismantlers compete over each other by offering higher prices to ELV as in the Chinese ELV market (Hu and Wen, 2015). The price competition may eventually lead the weaker players out of the market. The informal dismantlers are facing problems from the formalization of the recycling markets. For example, Steuer et al. (2018) report that the informal waste electric and electronic equipment (WEEE) recyclers in China are facing challenges with decreasing profits due to fluctuating commodity prices, competition with formal and informal counterparts, and increasing regulatory pressure from the government.

Even though SD models focus on various aspects of ELV recycling, they model at an aggregate level. The strategies proposed by Zamudio-Ramirez (1996) and Bandivadekar et al. (2004) for dismantlers to mitigate the reduction in profitability due to changing vehicle material composition or Amaral et al. (2006) and Inghels et al. (2016) to meet the regulatory targets ignore any inter-firm interactions. Similarly, Chen et al. (2015), Wang et al. (2014), and Mohamad-Ali et al. (2018) analyze the impact of various government policies on the ELV recycling system on a national level, but ignore any reactive strategies from the existing informal recyclers. The previous studies consider the strategies for ELV dismantlers or recyclers as a whole but ignored any interaction such as competition or cooperation that develops between various agents in the ELV management system.

When firms compete they make decisions that not only affect their state in a system but also affect the state of the entire system, i.e., market (Rahmandad and Spiteri, 2015). The decisions of one firm affect not only the payoffs of that firm but also the payoffs of the competitors that in turn affect the whole system. The effects of firms' decisions may also involve time delays, which make the competition a complex problem for analysis. Complex systems require a holistic analysis that is enabled by SD modeling. Though SD models generally focus on an aggregate market level, a few consider the inter-firm interactions in competition. Sice et al. (2000) use SD modeling to analyze the competition in a duopoly where the firms compete on quality to achieve a higher market share and they analyze the emerging behavior of the system and find that the system has a chaotic behavior. Brady (2009) develops a dynamic model of a Cournot duopoly, where the firms' competition is driven by advertising and analyzes the firms' behavior at high and low levels of advertising effectiveness. Rahmandad and Sibdari (2012) consider competition between two identical firms in a software market to analyze the effect of openness and pricing decisions on new software products on the profitability of the firms and provide recommendations for various scenarios. Thus the SD models of inter-firm competition recommend ideal strategies for competing firms.

The SD models of inter-firm competition deal with an oligopoly/duopoly setting where the sellers compete with each other, whereas our model focus on an oligopsony market focusing on the competition between buyers. We develop a system dynamics model to analyze the dynamic nature of oligopsonistic competition in ELV recycling markets and understand the effect of competition in the sustainability of the dismantling industry. In this paper, we consider the situation similar to the Indian ELV recycling market where currently there is one formal dismantler — 'Cero Recycling' just beginning the operations and a large number of informal dismantlers. We aim to model the dynamic competition between one formal dismantler and other informal dismantlers in an ELV recycling market. We aim to predict the effect of this competition on the market price of ELV, the profitability of the dismantlers, and the aggregate dismantling capacity. The simulation considers the price competition between the dismantlers in the market of end-of-life passenger cars taking into account the dynamics of steel scrap prices. In the competition, the dismantler with the higher price receives the major share of ELV (constrained by capacity), where we adapt the rationing rule of the Kreps-Scheinkman competition model (Kreps and Scheinkman, 1983) to allocate the ELVs to the dismantlers in the decreasing order of prices. The simulation results show that the competition leads to the higher market price for ELV, but a lower profit for dismantlers and reduced aggregate dismantling capacity with the exit of informal dismantlers. But, the competition is seen to be dampening occasionally due to *dismantlers' dilemma*. Furthermore, the higher the capacity of the formal dismantler, the faster the exit of informal dismantlers thereby diminishing the effects of competition resulting in the lower market price for ELV and reduced aggregate dismantling. The model results propose vertical integration of ELV management systems and vehicle manufacturers to ensure a competitive price to the ELV as well as a closed-loop supply of scrap. This is in concurrence with the latest developments of the Indian ELV industry as 'Maruti Suzuki Toyotsu India Private Limited', a joint venture of Maruti Suzuki Limited and Toyota Tsusho (Economic Times Auto, 2019) and Tata Steel a sister company of Tata Motors (tatasteel.com, 2019) are also venturing into the market. There is a dearth of literature analyzing competition in oligopsony markets and to the best of our knowledge, this the first model to capture the dynamic competition between formal and informal dismantlers in an ELV recycling market.

This paper is organized as follows: Section 2 explains the theory, method, and system dynamics model. Section 3 provides the results of the system dynamics simulation model. Section 4 discusses the managerial and policy implications of the model and Section 5 concludes the paper.

2. Methods

In this section, we provide the details of the system dynamics model used in our study. Section 2.1 explains the market setting and provides theoretical support for the system dynamics model developed. Section 2.1 gives the scope of the problem, describes the various relationships identified in the system, provides the system dynamics model and explains the various decision rules that govern the model.

2.1. Market setting

In the market under consideration, the owners of the ELVs are the sellers and the formal dismantler and informal dismantlers are the buyers. The product, ELV is sold by the ELV owners to the dismantlers in exchange for the price offered to the ELV. The number of sellers is very large compared to the buyers. As the informal dismantling market is assumed to be perfectly competitive, each dismantler is homogeneous (with the same capacity) and offers the same price for ELV. The formal dismantler has a fixed dismantling capacity, whereas the total informal dismantling capacity may vary with the entry and exit of informal dismantlers. The formal and informal dismantlers compete over each other by increasing the price of ELV to capture the maximum share of ELVs. We identify the market setting as an oligopsony with price competition.

The market setting is an imperfect competition where the agents' actions are influenced by the rivals' reactions. This leads to interdependence in agents' decisions and dynamic nature to the competition. In this competition, we assume that both the competitors conjecture the opponent may not deviate from their prices offered to ELV in the equilibrium. But, on realizing that the competitor has increased the prices, the opponent initiates an increase in their offered prices. As the firms are better informed about their costs than their competitors (Hornig and Stadler, 2000), the dismantlers continue to increase the price offered to the ELV until they are profitable. Thus, the market behaves like two von-Stackelberg leaders competing over prices. The dismantler who increases the price of ELV will be able to procure the maximum amount of ELV, while the competitor is left with a lesser number. The dismantlers may compete to procure from the maximum ELVs that are available for dismantling. The rationale can be explained as that the formal dismantler would like to utilize the full dismantling capacity to benefit from economies of scale, whereas the competitive informal dismantlers want to capture the maximum ELVs among themselves. As the dismantler may be having capacity constrains to dismantle the ELVs, we assume the loser of the competition also being able to procure some ELVs for dismantling similar to the Edgeworth-Bertrand model of price competition (Kreps, 1990).

The price competition increases the cost incurred by the dismantlers that in turn affects their future profitability. The profitability of dismantling also affects the entry and exit of informal dismantlers, which alters the total dismantling capacity. The dismantlers generate their revenue from the sale of scrap. The price of steel scrap is subjected to fluctuations in demand and supply. The fluctuations in dismantling capacity bring fluctuations in the amount of scrap supply. As steel scrap form the main volume of vehicle scrap (about 60% of the weight of the vehicle body), the fluctuations in the price of steel scrap affects the revenue and profitability of dismantlers. The profitability also affects the dismantlers' ability to increment the prices in the future. Thus we develop an SD model to capture the dynamic effects of this competition. The details of the system dynamics model are as explained in the subsequent sections.

2.2. System dynamics model

The SD approach is iterative in nature (Sterman, 2010). However, the various steps involved in SD modeling can be summed up as: determining the scope of the problem, identifying the causal relationships and feedback loops in the system, development of the simulation model (stock-flow structure) by determining the decision rules, testing the model for consistency, accuracy, and validity, and evaluating the model for policy design. The software used for developing the system dynamics model in this paper is Vensim® Pro-Software (Version 6.4E).

2.2.1. Scope of the model

In this section, we define the model boundaries. As the model focuses on unregulated ELV recycling systems that are predominant in emerging economies, we use the data from an emerging economy, i.e. India. For calculating dismantlers' revenue, we consider vehicles of homogeneous nature, i.e., passenger cars as the material composition by weight differ among different vehicle types. The dismantlers' total scrap revenue is used in the analysis, but only the dynamics in steel scrap price is being considered for profit calculation. The steel scrap forms the major amount of scrap from the vehicle and historically steel scrap prices display fluctuations due to demand-supply gaps (Albertson and Aylen, 1996). To assess the dynamics of steel scrap prices, we assume a closed-loop flow of steel scrap taking into account the supply of steel scrap from ELV only. We also do not take into consideration any export or import of ELV and scrap.

2.2.2. Causal loop diagram and feedback loops

Fig. 1 show the causal loop diagram (CLD) of the model. In SD models, a CLD represents the interrelationships between the component members of the system. The variables are linked to each other by arrows with a '+' or '-' symbol. The '+' symbol indicates a marginal increase in the value of an affected variable for an increase of the causal variable, the '-' symbol indicates a marginal decrease in the value of an affected variable for an increase in the causal variable. For example, the variable 'ELV Market Price' is directed towards the variable 'ELV Availability' by an arrow with a '+' sign. This indicates that an increase in 'ELV Market Price' will lead to an increase in 'ELV Availability'. The double hatch lines over the connecting arrow indicate a time delay in the effect. While CLD is a simplified version of the SD model, the stock-flow structure provides a richer representation depicting the stocks, flows, and delays.

The causal relationships identified in the system under consideration can be summarized as follows. The increase in the sale of vehicles will lead to an increase in the number of ELVs. But the ELVs available for dismantling depends on the market price offered to the ELV by the dismantlers. The higher the market price, the greater the ELV availability for dismantling. The market price of ELV depends on the price of ELV offered by the formal and informal dismantlers, where they compete with each other by increasing the price of ELVs. Increasing prices for ELV decrease the profitability of dismantlers. Higher ELV dismantling increases the supply of steel scrap leading to a reduction in the market price of steel scrap that reduces the profitability of the dismantlers. The dismantlers' future ability to increase prices also depends on their profitability. While an increase in profitability of dismantling also favors the entry of informal dismantlers, the decreasing profitability paves way for their exit. The relationships between the system variables lead to the development of feedback loops that influence the behavior of the system. The feedback loops may be of two types: reinforcing and balancing. A reinforcing loop progresses the direction of change of state of a system variable and a balancing loop balances the change of state.

We observe the following feedback loops in the model:

1. Reinforcing loop, **R1** - **ELV Price competition**: ELV Formal Price $\uparrow \longrightarrow$ ELV Informal Price $\uparrow \longrightarrow$ ELV Formal Price $\uparrow$
The competition between the formal and informal dismantlers by increasing the price of ELV forms a reinforcing loop. The increase in the price of ELV will continue until one player withdraws from the competition.
2. Balancing loop, **B1** - **Informal Cost Loop**: ELV Informal Price $\uparrow$ $\rightarrow$ Informal Dismantling Cost $\uparrow$ $\rightarrow$ Informal Dismantling Profit $\downarrow$ $\longrightarrow$ ELV Informal Price $\downarrow$
The increase in price offered to ELV increases the cost of informal dismantler leading to reduced profits that further deters the price offered for ELV by the informal dismantler in future periods. The total cost incurred by an informal dismantler includes the cost of the ELV and the cost of dismantling. As the informal dismantlers hire and fire manual laborers for dismantling per ELV basis, the nature of the cost is linear. The details of cost calculation are provided in Appendix Section A.5 (Refer to Eqs. (A.63)–(A.65)).

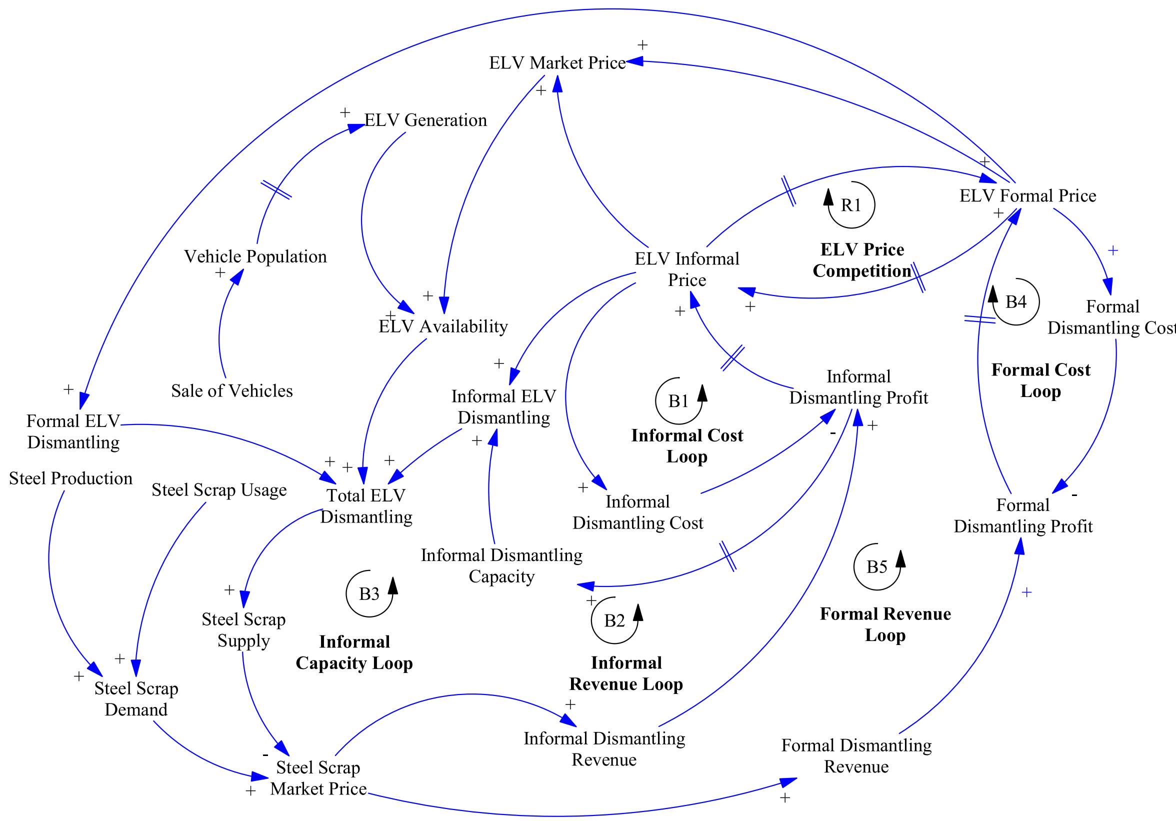

Fig. 1. System dynamics model: Causal loop diagram.

3. Balancing loop, **B2** - **Informal Revenue Loop**: ELV Informal Price ↑ → Informal ELV Dismantling ↑ → Total ELV Dismantling ↑ → Steel Scrap Supply ↑ → Steel Scrap Market Price ↓ → Informal Dismantling Revenue ↓ → Informal Dismantling Profit ↓ ⟶ ELV Informal Price ↓
   The increase in price offered to ELV increases the quantity of ELV dismantled by the informal dismantlers, which may lead to an increase in total dismantling and an increase in the supply of steel scrap. The increase in the supply of steel scrap will lead to a decrease in the market price of steel scrap thereby leading to reduced revenue and reduced profit that further deters the price offered for ELV by the informal dismantlers in future periods.
4. Balancing loop, **B3** - **Informal Capacity Loop**: Informal Dismantling Profit ↑ ⟶ Informal Dismantling Capacity ↑ → Informal ELV Dismantling ↑ → Total ELV Dismantling ↑ → Steel Scrap Supply ↑ → Steel Scrap Market Price ↓ → Informal Dismantling Revenue ↓ → Informal Dismantling Profit ↓
   An increase in informal dismantling profit favors the entry of more informal dismantlers. This may lead to increased informal dismantling and to increase in total dismantling that eventually leads to more scrap supply, fall in scrap prices, decreases revenue and profit for informal dismantlers. If the decrease in dismantlers revenue leads to losses, the informal dismantlers to gradually exit the market, thus form a balancing loop.
5. Balancing loop, **B4** - **Formal Cost Loop**: ELV Formal Price ↑ → Formal Dismantling Cost ↑ → Formal Dismantling Profit ↓ ⟶ ELV Formal Price ↓
   This loop works similarly as the Informal Cost Loop - B2, which balances the ELV price offered by the formal dismantler. The total cost incurred by the formal dismantler is calculated using the technical cost model developed by Ferrão and Amaral (2006). These include costs such as asset cost, maintenance cost, labor cost, and other variable costs. The asset cost includes the cost of land and machinery and the maintenance cost is calculated as a percentage of the asset cost. The asset cost and maintenance costs are assumed to be fixed components of the cost. The details of cost calculation are provided in Appendix Section A.4 (Refer to Eqs. (A.48)–(A.59)).
6. Balancing loop, **B5** - **Formal Revenue Loop**: Formal Dismantling Profit ↑ ⟶ ELV Formal Price ↑ → Formal ELV Dismantling ↑ → Total ELV Dismantling ↑ → Steel Scrap Supply ↑ → Steel Scrap Market Price ↓ → Formal Dismantling Revenue ↓ → Formal Dismantling Profit ↓
   This loop works similarly as the Informal Revenue Loop - B3, which balances the ELV price offered by the formal dismantler.

We build a stock-flow structure to run the simulation.

2.2.3. Stock-flow structure and decision rules

Fig. 2 represents the stock-flow structure of the model. SD model variables in a stock-flow structure can be classified into three as stock (box symbol), flow (valve symbol), and auxiliary (no symbol). Stocks are level variables that increase or decrease over time. Flows are rate variables that are either an input to or output from stocks that alter the level of stocks. Auxiliary variables may be independent or connected variables that may influence the flows.

As represented in the stock and flow structure, the variables are broadly classified into six groups, viz. *ELV estimation, ELV price competition, Dismantlers' revenue estimation, Formal dismantling, Informal dismantling*, and *Steel scrap price dynamics*. The model variables are explained in detail in Appendix A. We explain three mechanisms that are incorporated in the model viz. informal dismantler entry or exit, ELV price competition, and steel scrap price dynamics.

1. **Informal dismantler's entry and exit:** We use the mechanism put forward by Mohan and Amit (2020) for the entry and

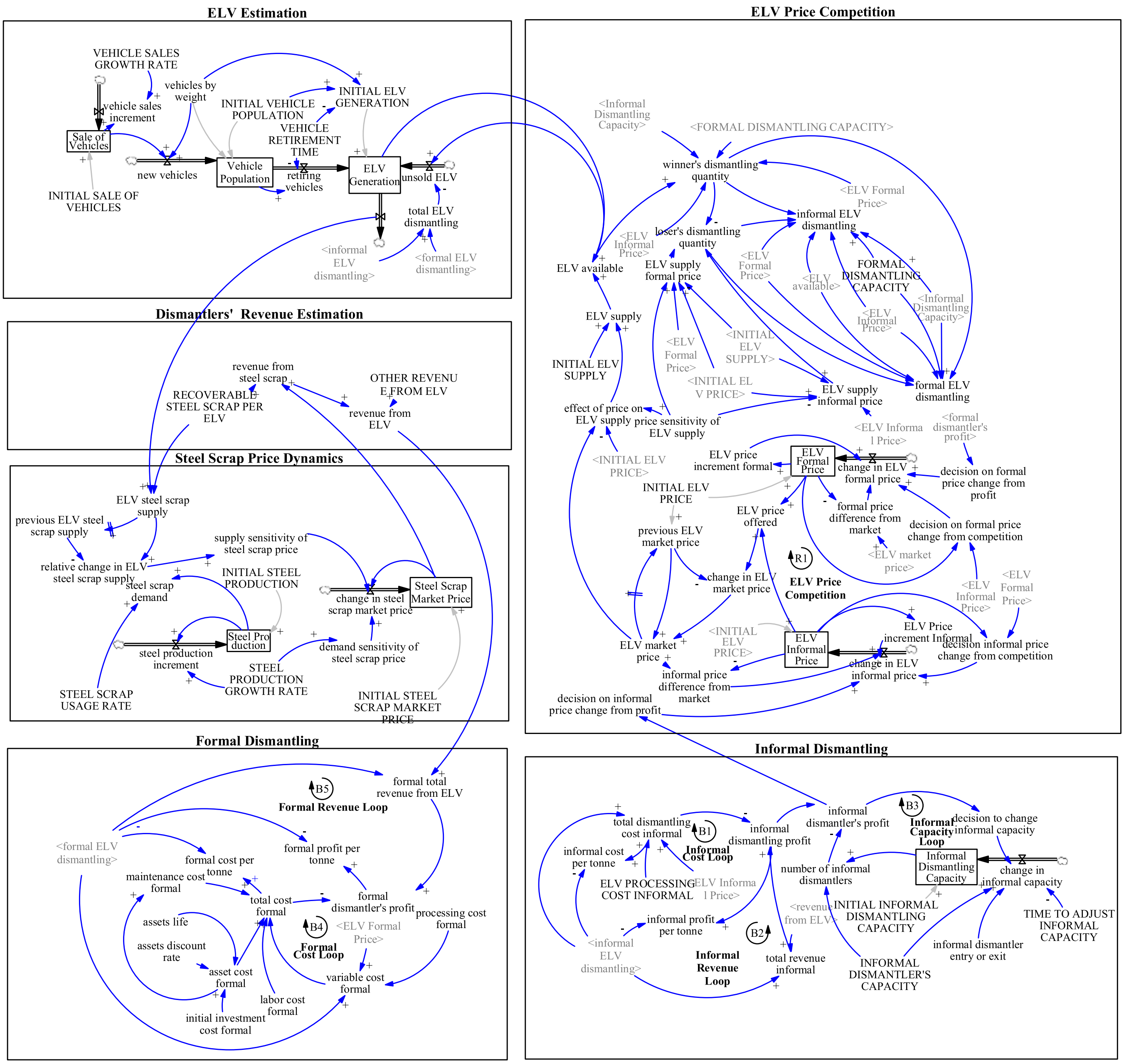

Fig. 2. System dynamics model: Stock-flow structure.

exit of informal dismantlers. They put forward the mechanism based on the assumption of the perfectly competitive market of informal dismantlers. In a perfectly competitive market of informal dismantlers, there are no barriers for entry and exit. New informal dismantlers enter when the current dismantlers are able to generate profits, and existing dismantlers exit when there are losses. They used the following rule model this mechanism: If the informal dismantlers generate positive profit from dismantling, one informal dismantler enters the system in the next period after receiving information about profitability. Similarly, when the informal dismantlers do not generate profit, one informal dismantler leaves the system in the next period (Refer to Appendix Section A.5, Eqs. (A.69)–(A.76)).

2. **ELV price competition:** The formal dismantler offer one price that is constant for the entire period and as the informal dismantlers are homogeneous they all offer the same price in a period. As the quantity of ELV generated may be limited compared to the available capacity, the dismantlers compete over each other on the price of ELV. The dismantlers increase their price to win over their competitors in price competition. We assume that they increment the price by a small percentage of their current price over the prevailing market price. The informal dismantlers are unorganized and have limited investment options (Akolkar et al., 2015). This prevents the informal dismantlers from making higher increments in their prices. Thus, in our model, we assume the informal dismantler makes a smaller increment than the formal dismantler.
The mechanism of price competition is given as:

$$\begin{aligned}&\text{If Current Price} \le \text{Competitor's Price},\\ &\text{New Price} = \text{Competitor's Price} + \text{Current Price} \times \delta\\ &\text{where, } \delta = \begin{cases} 0.05, & \text{for Formal Dismantler} \\ 0.01, & \text{for Informal Dismantler} \end{cases}\end{aligned} \quad (1)$$

(Refer to Appendix Section A.2, Eqs. (A.13)–(A.30)).

3. **ELV supply:** The supply of ELV available for dismantling depends on the price of ELV. We adapt the commodity market model proposed by Sterman (2010) for calculating the ELV supply at a particular period.

$$\text{ELV Supply} = \text{INITIAL ELV SUPPLY} \times \left(\frac{\text{ELV Market Price}}{\text{INITIAL ELV PRICE}}\right)^{\text{price sensitivity of ELV supply}} \tag{2}$$

'INITIAL ELV SUPPLY' and 'INITIAL ELV PRICE' are the amount of ELV available for dismantling and the market price of ELV at the beginning of the simulation. The market price of ELV is the maximum of the price offered by the formal and informal dismantlers. The price sensitivity of ELV supply gives the elasticity of ELV supply with respect to the price of the ELV. In this model we assumed the elasticity to be one. The assumption is made as in emerging economies the ELV owners are more sensitive to the price offered to ELV (Refer to Appendix Section A.2, Eqs. (A.31)–(A.35)).

4. **Rationing rules:** Rationing rules are applied when the availability of ELV is less than that of the existing dismantling capacity. We adopt the rationing rule used by Kreps and Scheinkman (1983). They consider the case of an oligopoly where the agents with a fixed capacity compete over prices. In their model, consumers purchase from the firm who demand lower price and if the market winner is constrained by capacity and not able to meet the entire demand, the consumers approach the other firms in the increasing order of prices. This rationing rule maximizes the consumer surplus in an oligopoly. We adopt a similar rationing rule in our model, where the ELV owners are willing to sell their ELV to the dismantler who offers a higher price. Once the capacity of the market winner is exhausted, ELV owners consider selling to the dismantlers who offer a lower price. The rationing rule is expressed as follows:
Let the dismantlers with capacities C_1 and C_2 offer prices P_1 and P_2 respectively and, let S_1 and S_2 be the supply of ELV generated for the respective prices, then the dismantling quantities obtained are given by Q_1 and Q_2. The rationing rule is as follows:

$$Q_1 = \begin{cases} \min(C_1, S_1) & P_1 > P_2 \\ \min(C_1, \max(0, S_1 - Q_2)), & P_1 < P_2 \\ \min(C_1, \max(\frac{S_1}{2}, S_1 - Q_2)), & P_1 = P_2 \end{cases} \tag{3}$$

The dismantler who offers the highest price will be able to purchase the ELVs first. They will purchase the ELVs no higher than their dismantling capacity. As the ELV owners are price sensitive, the other dismantler who offers the lower price will be able to purchase a lower quantity. When both the dismantlers offer the same price, they will dismantle the same amount of ELV, provided having enough capacity. Else the dismantler with higher capacity gets the opportunity to dismantle more than the competitor (Refer to Appendix Section A.2, Eqs. (A.36)–(A.43)).

5. **Steel scrap price dynamics:** As steel form the major constituent of a vehicle body, it also accounts for the largest amount of scrap recovered from an ELV. We consider the influence of demand-supply dynamics on scrap steel prices. Although the steel scrap from ELV forms only a part of the total steel scrap supply, we assume the scrap supply from ELV to influence the price of steel scrap. The price change is calculated as:

$$\text{New Price of Steel Scrap} = \text{Current Price} + \text{Current Price} \times (\text{Demand Effect on Price} - \text{Supply Effect on Price}) \tag{4}$$

'New price of Steel Scrap' is the price of steel scrap at the next period which is determined by the influence of demand-supply dynamics on the existing price (given by 'Current Price'). The demand effect of price is calculated from the expected increase in steel scrap usage due to increased steel production. The government of India has set a target for crude steel production of 255 million tonnes by the financial year 2030-31, which accounts for more than double the current production (Ministry of Steel, 2017). The supply effect of price is calculated as the relative change in steel scrap supply between the consecutive periods. Currently, the steel production in India is less reliant on steel scrap (Ministry of Steel, 2017). The scrap prices are more affected by the local market conditions. There is also an emphasis on boosting scrap-based steel production using the potential of the scrap generated from ELV (Ministry of Road Transport et al., 2016). Hence, we consider a closed-loop market for the ELV scrap to capture the dynamics of steel scrap prices (Refer to Appendix Section A.6, Eqs. (A.77)–(A.91)).

3. Results

The model is simulated for 120 months. The basic unit of time is taken as a month. The results discuss various effects of the price competition between the formal dismantler and informal dismantlers such as the market price of ELV, dismantling quantities, dismantlers' profitability, and the fluctuations in informal dismantling capacity. We also validate the model by structure-oriented behavior tests.

We discuss two cases: Case A and Case B. Case A is the base case where the model variables have values as defined in the Appendix and Case B analyzes the scenarios for different capacities of the formal dismantler. The initial conditions of both cases are detailed as follows:

- Case A: This case starts with the conditions similar to the year 2019 and is predicted for 10 years. The formal dismantler has a capacity that is equal to the initial ELV supply (10000 tonnes/month; Refer to Eq. (A.34)). This is in terms of the planned capacity of Cero Recycling (0.1 - 0.15 million tonnes/year; Refer to Eq. (A.48)). The initial aggregate informal dismantling capacity is 8000 tonnes/month (Refer to Eq. (A.75)). The initial price offered to the ELV is 18,750 (Indian Rupee/tonne, estimated from Mohan Ram et al., 2015 and Akolkar et al., 2015).
- Case B: In this case, we analyze for scenarios of various capacities of formal dismantler (Refer to Eq. (A.48)). With the other model variables remaining the same, the capacities of the formal dismantler are varied in scenarios that are greater than, equal to, or less than the current rate of ELV generation and informal dismantling capacity. We intend to find the effect of formal dismantler's capacity on the competition.

3.1. Case A

We analyze the behavior of the model variables related to the prices offered to ELV, dismantling quantities, profits of dismantlers, and the capacity of informal dismantlers. Fig. 3 plots the market price and prices offered by the formal and informal dismantlers to the ELV per period (In the graph, the series market price is hidden either by the series representing the prices offered by formal or informal dismantlers. The market price is given by the series that is the maximum of the two.). The initial fluctuations up to period 18 show that due to competition, the market price of ELV turns out to be either the price offered by formal or informal dismantler, whichever is maximum (Hereafter, we call this period, i.e. from 0 - 18 as the 'intense competition period'). In later stages, the market price of ELV turns out to be the price offered by the formal

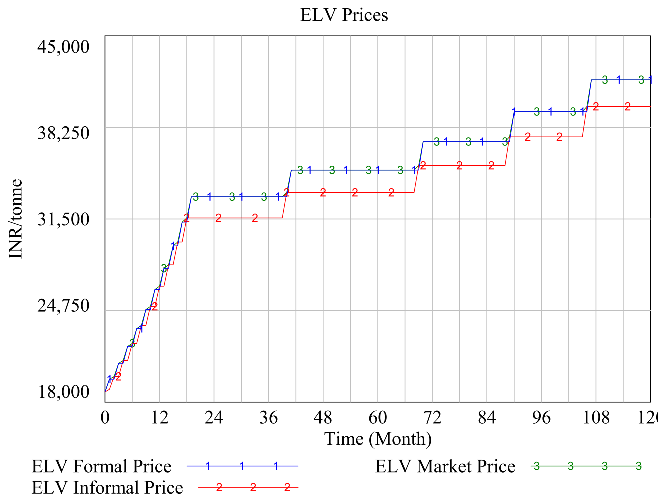

Fig. 3. Case A: ELV price (INR/tonne) forecasts over 10 years.

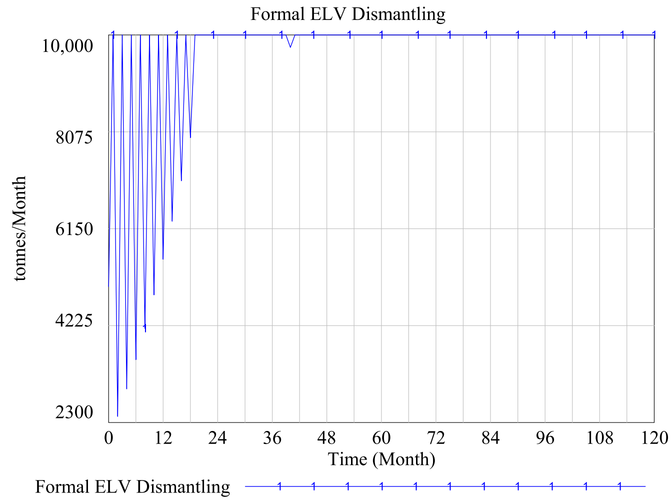

Fig. 5. Case A: Formal dismantling quantity (tonnes/month) forecasts over 10 years.

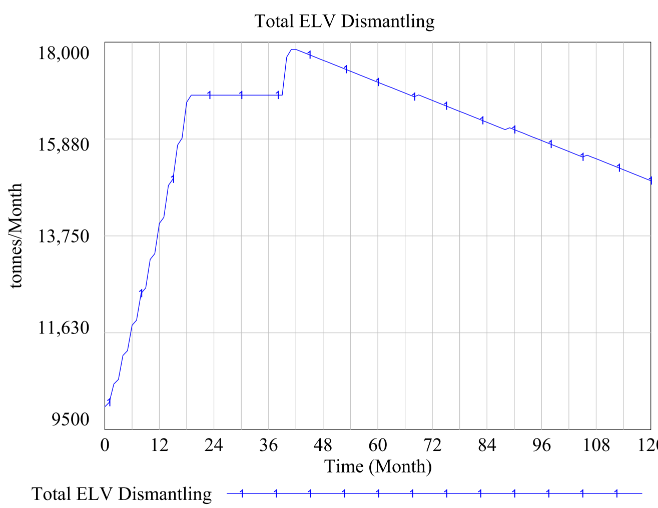

Fig. 4. Case A: Aggregate dismantling quantity (tonnes/month) forecasts over 10 years.

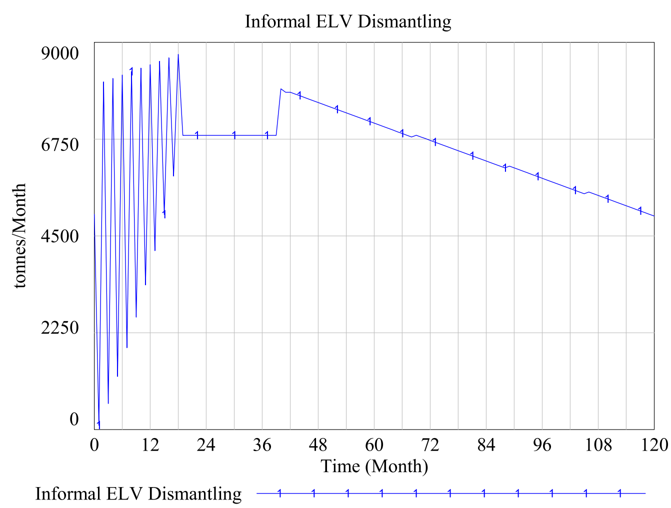

Fig. 6. Case A: Informal dismantling quantity (tonnes/month) forecasts over 10 years.

dismantler. A steady ELV price indicates that there is no competition over that period. This happens when the cost of dismantling exceeds the benefits for the informal dismantlers and they do not increase the prices. Thus, the formal dismantler has no incentive to increase the price of ELV in these instances. Even though the informal dismantler can offer the market price in some instances, the informal price generally lags behind the formal price.

Fig. 4 represents the aggregate amount of ELVs dismantled by the formal and informal dismantlers. The total quantity is found to be increased during the intense price competition. The competition increases the price of ELV and thereby ELV supply and also the total ELVs dismantled (Refer to Eq. (2)). On the contrary, the total dismantling quantity remains constant till period 39, followed by a small increase, then decreases around period 42 and shows a steady decline thereafter. We examine the dismantling quantities of formal and informal dismantlers to explain this behavior.

Figs. 5 and 6 give the total amount of ELVs dismantled per month by the formal dismantler and informal dismantlers respectively. During the intense competition period, the dismantler who offers a higher price can buy more quantity (constrained by their dismantling capacity) and the ELV available for the competitor will be low due to the lower price (Refer to Eq. (3)). The combined capacity available for dismantling is higher than the ELV supply at this stage. As a result, the dismantler who offers a lower price will get a lower quantity than the dismantler who offers the higher (market) price. This results in the initial fluctuations in dismantling quantities of formal and informal dismantlers. As the competition leads to an increase in the price of ELV, there is an increased number of ELVs available for dismantling to both the dismantlers. This explains the dampening trend of fluctuations in dismantling quantities of formal and informal dismantlers. The dip in informal dismantling quantity after the fluctuations corresponds to the lower availability of ELV due to the lower price offered by the informal dismantlers. This also corresponds to the constant aggregate dismantling quantity after intense competition until period 39 in Fig. 4. With an increase in price (Refer to Fig. 3), the informal dismantlers are again able to dismantle more, which explains the short increase in the informal dismantling quantity. This also corresponds to a small dip in the formal dismantling quantity after the initial fluctuations. But even with the price increase, informal dismantling quantity is declining in later stages, due to the reduction in total dismantling capacity with the gradual exit of informal dismantlers from the market as represented in Fig. 7. Initially, when informal dismantlers can generate profits, more informal dismantlers are attracted to the market. But the increasing price offered to ELV eventually lead the informal dismantlers into loss and they gradually exit the market. The intermittent but very small in-

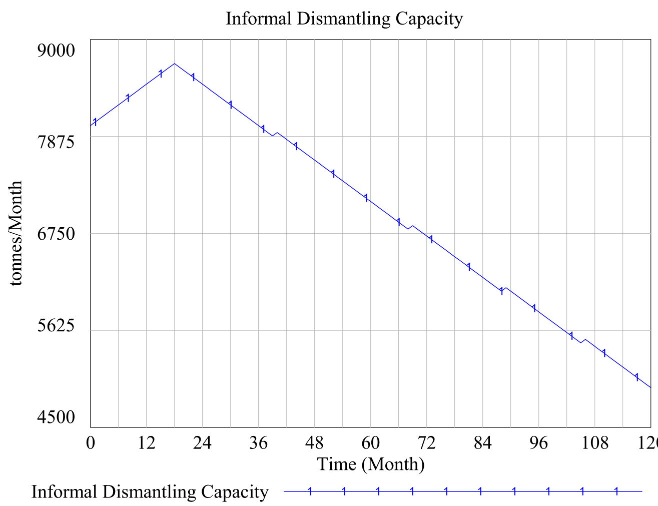

Fig. 7. Case A: Informal dismantling capacity (tonnes/month) forecasts over 10 years.

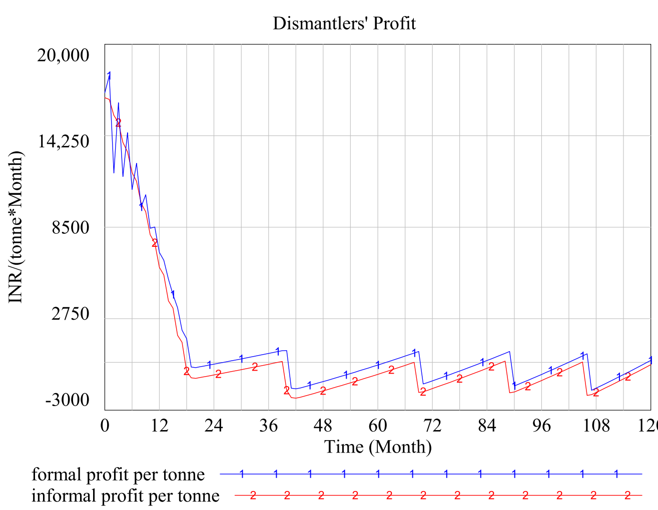

Fig. 8. Case A: Dismantlers' profit (INR/tonnes-month) forecasts over 10 years.

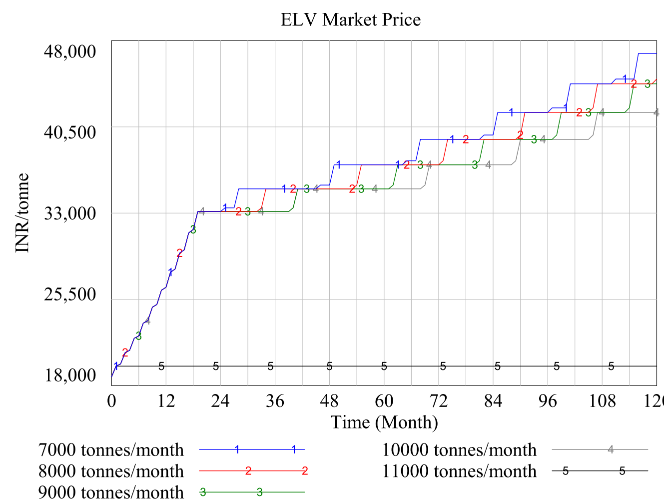

Fig. 9. Case B: ELV price (INR/tonne) forecasts over 10 years.

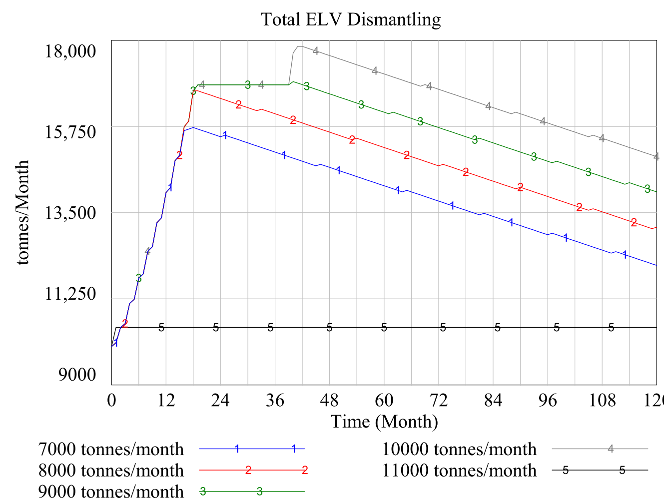

Fig. 10. Case B: Aggregate dismantling quantity (tonnes/month) forecasts over 10 years.

crease in informal capacity in the later stages is due to the entry of dismantlers. The informal dismantlers enter when the increase in prices of steel scrap makes the dismantling profitable at some later periods. With the exit of more informal dismantlers in later stages, the total dismantling quantity declines.

The profit per tonne generated by the formal and informal dismantlers is compared in Fig. 8. Competition affects the profitability of dismantlers, which shows a decreasing trend. The small and intermittent rises in profits can be attributed to the increase in the price of steel scrap. The exit of informal dismantlers from the recycling market leads to a deficiency of the supply of steel scrap that will increase the price of steel scrap in the market. When the dismantlers are profitable, price competition can happen, leading to an increased price of ELVs. The sudden decrease in profit followed by the rise is due to the increase in the price of ELVs due to competition. The fluctuations in the quantity of ELVs available for dismantling cause the initial fluctuations in profit for formal dismantler. The increasing price of ELV reduces the profit of ELV dismantlers and may even lead them to losses at times. The profitability of formal dismantler is observed to be better than informal dismantlers. This is due to the ability of the formal dismantler to achieve reduced cost with economies of scale when running on full dismantling capacity. But, the increased price of ELV undermines greater cost savings from economies of scale in the later stages. The informal dismantlers' profits decrease steadily and they rarely make positive profits.

From the results, we observe that the selected model variables display different behaviors before and after the period where the informal dismantlers start exiting the market. The initial fluctuations occur due to competition. But as the informal dismantlers gradually exit the market, the intensity of competition reduces the frequency of fluctuations. This can be attributed to the increased price of steel scrap due to the reduction in total dismantling quantity with the exit of informal dismantlers. As the scrap price increases, the dismantlers can improve their profits and the price competition tends to continue in the market until the informal dismantlers are present in the market.

3.2. Case B

In this case, we analyze various capacities for the formal dismantler. We aim to find an ideal installed capacity for the formal dismantler. The following scenarios as represented in Table 1 are analyzed.

The results of the analysis are plotted in Figs. 9–12. Fig. 9 gives the market price of ELV, Fig. 10 represents the combined quantity of ELVs dismantled by the formal and informal dismantlers,

Table 1
Case B: Scenarios for various capacities of the formal dismantler.

Sl. No.	Scenario	Formal dismantler's capacity (Tonnes/Month)
1	Formal capacity equals to the initial ELV supply	10,000
2	Lower than the initial ELV supply and lower than initial informal capacity	7000
3	Lower than the initial ELV supply and equal to initial informal capacity	8000
4	Lower than the initial ELV supply and higher than initial informal capacity	9000
5	Higher than the initial ELV supply	11000

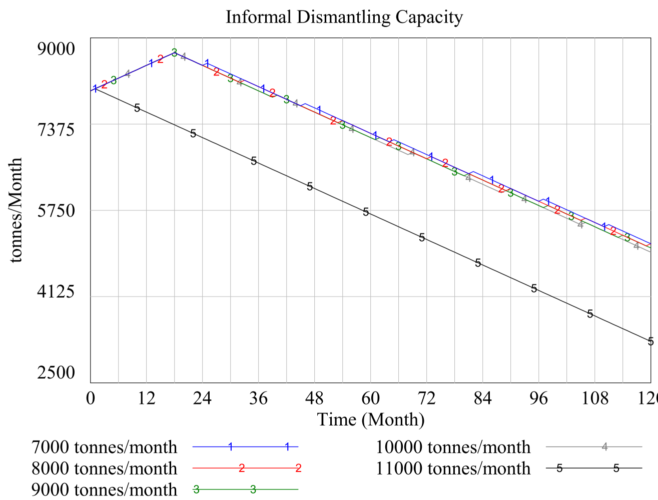

Fig. 11. Case B: Informal dismantling capacity (tonnes/month) forecasts over 10 years.

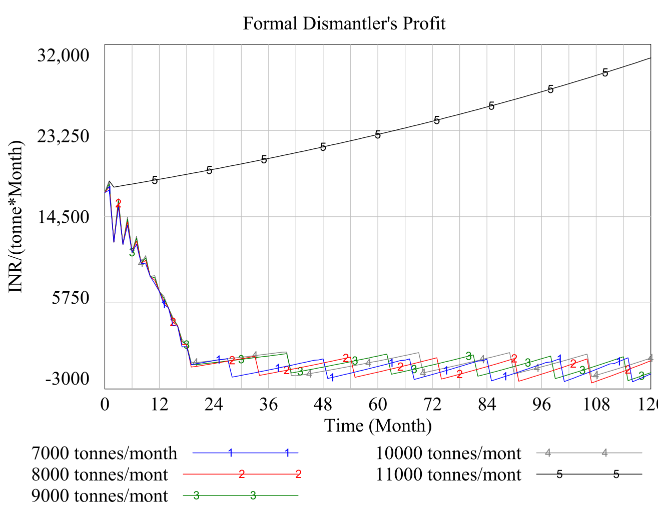

Fig. 12. Case B: Formal dismantler's profit (INR/tonnes-month) forecasts over 10 years.

Fig. 11 represents the change in informal dismantling capacity and Fig. 12 represent the profit per tonne of formal dismantler in various scenarios. We observe similar patterns of behavior as in Case A, in scenarios where the formal dismantling capacity is less than or equal to the initial ELV supply, whereas when the formal capacity is greater than the initial ELV supply, the competition stops after the first period and the informal dismantlers withdraw from the market. Thus, in this section, we explain the above scenarios separately.

In scenarios where the formal dismantling capacity is less than or equal to the initial ELV supply, informal dismantlers begin to exit the market when they start to generate losses as similar to Case A. Though relatively small in magnitude, the higher the capacity of formal dismantler, the greater the exit of informal dismantlers. The rate of increase in the ELV market price appears to be the same until informal dismantlers exit the market. Following that, lower the capacity, faster the increments in market price, and higher the market price. We observe that aggregate ELV dismantling quantity is the same during the initial stages of the competition and after the informal dismantlers begin to exit, the higher the formal dismantling capacity, the higher the total dismantling quantity. As the market price of ELV exhibits an inverse relation with the increase in formal dismantling capacity, the rise in total ELV dismantling is solely due to the higher formal dismantling quantity. The formal dismantler's profit fluctuates as in similar to Case A and is observed to be comparatively higher for higher dismantling capacities. This can be attributed to advantages from economies scale due to higher capacity and reduction in costs from reduced ELV prices. Thus, a higher capacity provides a competitive advantage for formal dismantler.

When the formal dismantler has a sufficiently high capacity than the initial ELV supply, the price competition ends after the first period. This will lead to the formal dismantler being able to capture all the ELVs for dismantling leaving the informal dismantlers deprived of dismantling. Thus, the absence of competition leads to only the formal dismantler performing dismantling leading to uniform dismantling quantity in all periods after the first period. The formal dismantler can generate higher profits as time progresses. This is because there is no increase in the price offered to ELV and an increase in steel scrap price due to increased demand together with no increase in the supply of steel scrap with the constant rate of ELV dismantling.

The model is tested for its consistency and accuracy and is explained in Section 3.3.

3.3. Testing and validation of the model

We conduct a structure-oriented behavior test to check the accuracy of decision rules governing the model. This test is recommended to detect any structural flaws in SD models and can be conducted by testing the model behavior in extreme conditions by assigning extreme values to the model variables (Barlas, 1996). The model is tested for a situation of extreme conditions where the dismantlers do not compete with each other. This situation is incorporated in the model by making the formal and informal dismantlers keeping their offered prices unchanged to any changes in competitor's price. The results of the extreme condition are then compared with the results of Case A.

As seen in Fig 13, in the absence of competition, the price of ELV remains unchanged. When the price of ELV remains constant, the number of ELVs available for dismantling also remains constant. Thus, the total number of ELVs dismantled remains the same (Fig. 14). As the formal dismantler is having a capacity that is equal to the initial ELV supply, the price of ELV as well the quantity of ELVs dismantled remains the same throughout the simulation. Thus, the model is validated.

The model provides many implications for policymaking. They are as discussed in Section 4.

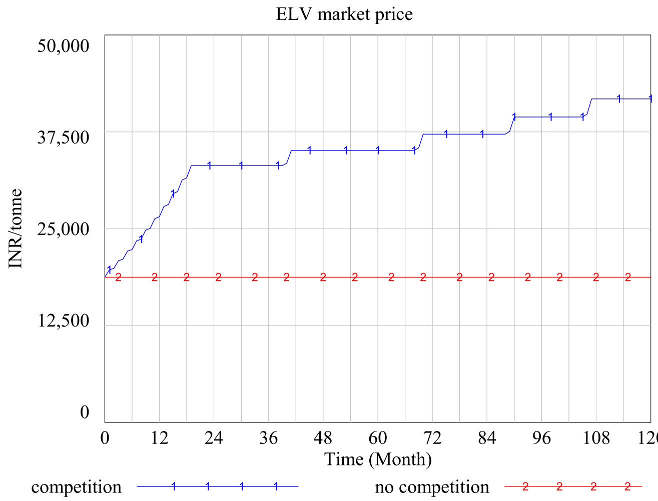

Fig. 13. Validation: ELV price (INR/tonne) forecasts over 10 years.

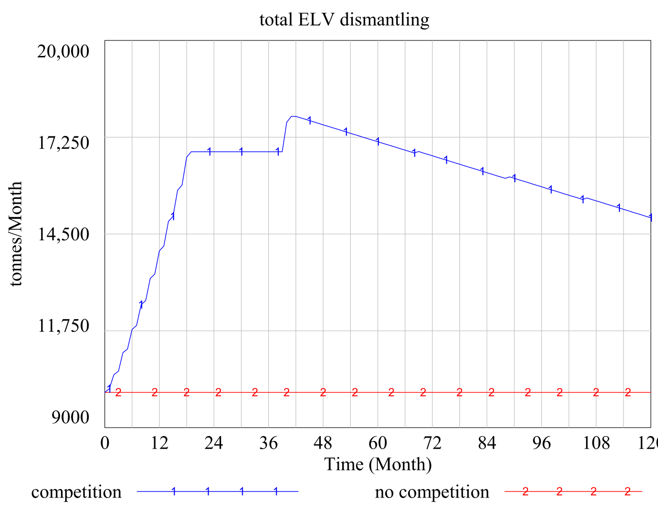

Fig. 14. Validation: Aggregate dismantling quantity (tonnes/month) forecasts over 10 years.

4. Discussion

This study contributes to the literature of dynamic analysis of ELV recycling systems. Also, this study provides managerial implications for setting up a closed-loop supply chain of ELV and provides policy implications for the effective functioning of the system. The presence of formal and informal dismantlers in an ELV recycling market leads to competition. This competition is noticeable in emerging economies where informal dismantlers dominate and a few formal dismantlers are present. The dismantlers compete with each other offering higher prices to ELV. This paper studies the competition in an unregulated ELV recycling market, where one formal dismantler and many informal dismantlers exist. We develop a system dynamics model to understand the dynamic effects of competition in the recycling market. We use the data from the Indian market where one formal dismantler, ‘Cero Recycling’, and many informal dismantlers are present. We also analyze the scenarios for various dismantling capacities of the formal dismantler.

The simulation results show that the competition leads to higher prices for ELV. The market price of ELV tends to follow the price offered by the formal dismantler in the long term and the rise in the market price of ELV is lower for higher capacities of formal dismantler. In the base case, the market price of ELV has grown over 200% in 10 years. The profitability of both formal and informal dismantlers are impacted by the price competition. The formal dismantler can make better profits than the informal dismantlers due to the cost savings from economies of scale. With decreasing profitability, the informal dismantlers gradually exit the market and the informal dismantling capacity reduces to 50% in 10 years. This leads to a reduction in aggregate ELV dismantling capacity. The entry and exit of dismantlers due to the competition causes fluctuations in the supply of steel scrap which in turn causes fluctuations in steel scrap prices. The fluctuations in scrap prices affect the profitability of both formal and informal dismantlers.

4.1. Managerial implications

Vertical integration of dismantling and shredding units with scrap processing units helps in arresting the fluctuations in scrap prices. It will be beneficial in the long term for the vehicle manufacturers if they are integrated with end-of-life processing units, as it enables them to control the supply and price of materials for manufacturing. This helps in a closed-loop flow of materials in the vehicle industry. For example, Toyota in Japan has coordinated with dismantlers and other vehicle manufacturers for dismantling and formed a company ‘Toyota Metal Company’ to recycle materials from automotive shredder residue (ASR) (toyota global.com, 2014). The lone formal ELV dismantler in India -‘Cero Recycling’, is a joint venture with ‘Mahindra Accelo’ (a steel processing company) and MSTC Limited (formerly Metal Scrap Trade Corporation Limited a scrap collecting company of the government of India) (cerorecycling.com, 2020). The parent company of ‘Mahindra Accelo’, ‘Mahindra’ is a vehicle manufacturer. More vehicle manufacturers in India are following the same strategy. Maruti Suzuki Limited the biggest carmaker of India has formed a vehicle dismantling and recycling company, a joint venture with Toyota Tsusho named Maruti Suzuki Toyotsu India Private Limited (MSTI) (Economic Times Auto, 2019). The company is expected to commence its operations in the year 2021.‘Tata Steel’ a subsidiary of ‘Tata Group’ also plans to set up a scrap-based steel plant in India (tatasteel.com, 2019). The group also owns ‘Tata Motors’, a vehicle manufacturer.

Recycling clusters comprising of many vehicle dismantlers and scrap processing units can be formed on the lines of automobile clusters (Mohan Ram, 2018). Automobile clusters are being characterized by the presence of many vehicle manufacturers and suppliers. When vehicle manufacturers own end-of-life management systems, the recycling clusters can be integrated with their raw material suppliers enabling greater vertical integration of vehicle manufacturers and end-of-life management systems. Also, the presence of multiple recyclers in a cluster may facilitate recycling coalitions where the recyclers can share recycling technology, resources, and reverse logistic channels that reduce the fixed costs of establishing recycling infrastructure (Tian et al., 2020). Foreseeing these potential benefits, the government of India is planning to set up automobile clusters comprising recycling plants near ports in India (Press Trust of India, 2020).

4.2. Policy implications

The simulation results also show that the higher the capacity of formal dismantler, the higher the dismantling quantities and profit for the formal dismantler and vice versa for the informal dismantlers. When the formal dismantler installs a high capacity that is higher than the current rate of ELV generation, they will be able to abate competition and capture the full supply of ELV, leading to the rapid exit of informal dismantlers from the market. The entry of formal dismantlers to the market with a sufficiently high capacity drive out the informal dismantlers faster creating a *monopsony* market. In this scenario, the formal dismantlers have no incentive to increase the price that will lead to lesser aggregate ELV dismantling. This necessitates the use of certain economic and/or policy instruments to generate more ELV supply in concurrence with installing more capacity. The efficiency of policy instruments will increase if vehicle manufacturers are integrated with end-of-life management units. For example, the government of India has proposed a Voluntary Vehicle fleet Modernization Programme (V-VMP) to provide incentives for buying new vehicles upon delivering the old vehicle to formal dismantlers (Ministry of Road Transport et al., 2016). If the vehicle manufacturer owns or coordinates with an ELV management system, they can ensure more sales of their new vehicle by offering better incentives to the older vehicles. Arora et al. (2019) proposes a business model under a shared responsibility framework for sustainable ELV management in India. They propose the usage of instruments such as advanced recycling fees from vehicle manufacturers for setting up the ELV management system. This instrument will also perform better if vehicle manufacturers are vertically integrated with end-of-life management systems.

The competition benefits the ELV owners as they receive higher prices for the ELVs. But in the long term, the competition reduces the profit of formal and informal dismantlers. Policy intervention generally favors the formal dismantler, as government subsidies or incentives are not applicable for the informal dismantlers. The alignment of policies is necessary as the formal dismantling will lead to a more environmentally friendly process with reduced dumping of waste. But, as the current informal dismantling in India generates a lot of direct and indirect employment, the exit of informal dismantlers will lead to the loss of these employment opportunities. Policymakers have to see the trade-off between environmental and social sustainability. As the formal dismantling requires a lot of investment to set up, policies to convert the current informal dismantling units to formal units and the possibilities of vehicle manufacturers' involvement in this venture need to be looked into.

5. Conclusions

To the best of our knowledge, this paper is the first attempt to conduct a dynamic analysis of competition in ELV recycling markets. A system dynamics model is developed to analyze the competition between a formal dismantler and informal dismantlers in an unregulated ELV recycling market. With, the entry of formal dismantlers in an unregulated ELV recycling market, the formal and informal ELV dismantlers compete over the prices of ELV that adversely affects the profitability of dismantlers. The informal dismantlers are more affected by the competition that leads to their gradual exit from the market. The informal dismantling capacity reduces to about half of the existing capacity over 10 years. This, in turn, reduces total dismantling capacity and leads to less supply of scrap for recycling. The higher capacity provides the formal dismantler a competitive advantage leading to a rapid exit of informal dismantlers. As formal dismantlers perform environmentally sound practices in comparison to informal dismantlers, we recommend policymakers to provide more support to them. This can be achieved through designing policy instruments that persuade vehicle manufacturers to establish formal dismantling centers, thereby establishing a closed-loop flow of materials in the automobile supply chain.

This research can be extended in multiple dimensions. Some additional factors can be taken into account when modeling the competition between the single formal dismantler and informal dismantlers. The formal dismantlers may consider purchasing ELVs and keeping them as inventory to dismantle in the future. Also, the formal dismantler may consider expanding the plant capacity to dismantle the increasing supply of ELVs. A dynamic optimization problem of competition can be developed to estimate the optimum level of capacity and inventory taking into consideration the relevant costs.

The model in this paper considers the competition between a single formal dismantler and multiple informal dismantlers. The scenario of entry of multiple formal dismantlers and the subsequent effects on the competition can be analyzed. The models can also consider the effect of variations in dismantling cost for the formal dismantler. The formal dismantler might incur a compliance cost when the ELV market gets regulated. The model can be extended by considering the changing regulatory environment. The cost of dismantling may also get affected by the impact of technological changes in ELV recycling. Technological changes can happen with the development of new vehicle fleet such as electric vehicles or developments in recycling technologies. Currently, scrap-based steel production in India is lower compared to many other countries. ELVs can form a major source for steel scrap if policies for enhancing ELV recycling is aligned with targets for scrap-based steel production. Models can be developed to test and analyze the effectiveness of policy alternatives in this regard.

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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.

Appendix A. Model variables

The variables in the stock and flow structure of the model are described as follows:

A1. ELV estimation

This section defines the variables used to estimate the amount of ELVs generated. The model is based on Indian data. The unit of analysis is the passenger cars in India.

$$\text{INITIAL SALE OF VEHICLES} = 280000 \quad \text{Units: Vehicles/Month} \tag{A.1}$$

'INITIAL SALE OF VEHICLES' refers to the monthly vehicle sales at the beginning of the planning horizon of the simulation. The data corresponds to the sale of passenger cars in India provided by the Society of Indian Automobile Manufacturers (SIAM) (Society of Indian Automobile Manufacturers, 2020).

$$\text{VEHICLE SALES GROWTH RATE} = 0.0017 \quad \text{Units: Dimensionless} \tag{A.2}$$

'VEHICLE SALES GROWTH RATE' is the compounded annual growth rate (CAGR) of vehicles. The CAGR used in this model is that of passenger car sales of India from the period 2011-12 to 2018-19 and we assume the same CAGR to continue for the planning horizon. As the basic unit of time is one month, the CAGR is adjusted for monthly calculations.

$$\text{Sale of Vehicles} = \text{INITIAL SALE OF VEHICLES} + \int_0^t (\text{vehicle sales increment}) \times dt \quad \text{Units: Vehicles/Month} \tag{A.3}$$

$$\text{vehicle sales increment} = \text{Vehicle Sales} \times \text{VEHICLE SALES GROWTH RATE} \quad \text{Units: Vehicles/Month} \tag{A.4}$$

Similar to many emerging economies, vehicle sales in India follows an increasing trend. The growing vehicle sales are calculated with the help of variables 'vehicle sales increment' and 'VEHICLE SALES GROWTH RATE'. The variable 'Sale of Vehicles' gives the sale of vehicles at a particular period. The vehicle sales are modeled as a stock variable to incorporate the change/increase in vehicle sales over the periods.

$$\text{new vehicles} = \text{Sale of Vehicles} \times \text{vehicles by weight} \quad \text{Units: Tonnes/Month} \tag{A.5}$$

$$\text{vehicles by weight} = 0.8 \quad \text{Units: Tonnes} \tag{A.6}$$

'new vehicles' give the vehicles in equivalent to the amount of scrap covered by ELV. In the current model, we consider the ELV as equivalent to the weight of scrap recovered from each ELV. 'vehicles by weight' gives the maximum amount of useful scrap recovered from an ELV (Mohan Ram et al., 2015).

$$\text{Vehicle Population} = (\text{INITIAL VEHICLE POPULATION} \times \text{vehicles by weight}) + \int_0^t (\text{new vehicles - retiring vehicles}) \times dt \quad \text{Units: Tonnes} \tag{A.7}$$

$$\text{INITIAL VEHICLE POPULATION} = 30000000 \quad \text{Units: Vehicles} \tag{A.8}$$

'Vehicle Population' gives the number of vehicles that are currently active. The vehicle population increases with the new vehicles entering the road and decreases with the vehicles being termed as ELV. In our model, we consider the vehicles that have reached a particular age as ELV denoted by the variable 'VEHICLE RETIREMENT TIME'. '"INITIAL VEHICLE POPULATION' represents the total number of vehicles that are active at the beginning of the planning horizon, estimated from the vehicle registration data provided by the Government of India (data.gov.in, 2017).

$$\text{VEHICLE RETIREMENT TIME} = 180 \quad \text{Units: Month} \tag{A.9}$$

'VEHICLE RETIREMENT TIME' gives the average time taken for a passenger car to reach the status of an ELV. This average time is estimated as 15 years or 180 months by CPCB, India (Central Pollution Control Board (CPCB), 2016).

$$\text{retiring vehicles} = \frac{\text{Vehicle Population}}{\text{VEHICLE RETIREMENT TIME}} \quad \text{Units: Tonnes/Month} \tag{A.10}$$

'retiring vehicles' represents the number of vehicles reaching ELV status per period. Due to variations in usage or accidents or due to the discretion of the user, all vehicles sold together may not reach the status of ELV simultaneously. Therefore, we model the vehicle retirement as a first-order delay similar to Inghels et al. (2016).

$$\text{ELV Generation} = \text{INITIAL ELV GENERATION} + \int_0^t (\text{retiring vehicles + unsold ELV - total ELV dismantling}) \times dt \quad \text{Variable type: Stock} \quad \text{Units: Tonnes} \tag{A.11}$$

$$\text{INITIAL ELV GENERATION} = \frac{\text{INITIAL VEHICLE POPULATION} \times \text{vehicles by weight}}{\text{VEHICLE RETIREMENT TIME}} \quad \text{Units: Tonnes} \tag{A.12}$$

'ELV Generation' is the total stock of vehicles that have reached the status of an ELV. The inflows 'retiring vehicles' and 'unsold ELV' add to the ELV stock whereas the outflow 'total ELV dismantling' reduces the stock of ELV. 'INITIAL ELV GENERATION' gives the amount of ELVs at the beginning of the simulation, which is calculated from 'INITIAL VEHICLE POPULATION' in a similar way as calculating 'retiring vehicles'.

A2. ELV Price competition

This section explains the variables that describe the price competition between formal and informal dismantlers.

INITIAL ELV PRICE = 18750 (A.13)
Units: INR/Tonne

'INITIAL ELV PRICE' refers to the price per tonne offered to an ELV at the beginning of the planning horizon. This is the current price offered by the informal dismantlers. In our model we assume formal and informal dismantlers to offer the same price at the beginning of the simulation.

$$\text{ELV Formal Price} = \text{INITIAL ELV PRICE} + \int_0^t (\text{change in ELV formal price}) \times dt \quad \text{(A.14)}$$
Variable type: Stock
Units: INR/Tonne

'ELV Formal Price' gives the price of ELV that can be offered by the formal dismantler. 'change in ELV formal price' gives the change in the price of ELV offered by the formal dismantler due to competition.

$$\text{ELV Informal Price} = \text{INITIAL ELV PRICE} + \int_0^t (\text{change in ELV informal price}) \times dt \quad \text{(A.15)}$$
Variable type: Stock
Units: INR/Tonne

'ELV Informal Price' gives the price of ELV that can be offered by the informal dismantler. 'change in ELV informal price' gives the change in the price of ELV offered by the informal dismantler due to competition.

The formal dismantler offers one price that is constant for the entire period and as the informal dismantlers are homogeneous they all offer the same price in a period. As the quantity of ELV generated may be limited compared to the available capacity, the dismantlers compete over each other on the price of ELV.

$$\text{ELV price increment formal} = 0.05 \times \text{ELV Price Formal} \quad \text{(A.16)}$$
Units: INR/Tonne

$$\text{ELV price increment informal} = 0.01 \times \text{ELV Price Informal} \quad \text{(A.17)}$$
Units: INR/Tonne

'ELV price increment formal' and 'ELV price increment informal' gives the increment in the current price of ELV offered by formal and informal dismantlers respectively.

$$\text{formal price difference from market} = \text{ELV market price} - \text{ELV Price Formal} \quad \text{(A.18)}$$
Units: INR/Tonne

$$\text{informal price difference from market} = \text{ELV market price} - \text{ELV Price Informal} \quad \text{(A.19)}$$
Units: INR/Tonne

'formal price difference from market' and 'informal price difference from market' represent the difference in formal and informal dismantlers offered price of ELV from the prevailing market price.

$$\text{decision on formal price change from profit} = \begin{cases} 1, & \text{if formal dismantler's profit} > 0 \\ 0, & \text{otherwise} \end{cases} \quad \text{(A.20)}$$
Units: Dimensionless

$$\text{decision on informal price change from profit} = \begin{cases} 1, & \text{if informal dismantler's profit} > 0 \\ 0, & \text{otherwise} \end{cases} \quad \text{(A.21)}$$
Units: Dimensionless

$$\text{decision on formal price change from competition} = \begin{cases} 1, & \text{if ELV Price Formal} \le \text{ELV Price Informal} \\ 0, & \text{otherwise} \end{cases} \quad \text{(A.22)}$$
Units: Dimensionless

$$\text{decision on informal price change from competition} = \begin{cases} 1, & \text{if ELV Price Informal} \le \text{ELV Price Formal} \\ 0, & \text{otherwise} \end{cases} \quad \text{(A.23)}$$
Units: Dimensionless

TIME TO ADJUST ELV PRICE = 1 (A.24)
Units: Month

$$\text{change in ELV formal price} = ((\text{formal price difference from market} + \text{ELV price increment formal}) \times \text{decision on formal price change from competition} \times \text{decision on formal price change from profit}) \div \text{TIME TO ADJUST ELV PRICE} \tag{A.25}$$
Units: INR/Tonne-Month

$$\text{change in ELV informal price} = ((\text{informal price difference from market} + \text{ELV price increment informal}) \times \text{decision on informal price change from competition} \times \text{decision on informal price change from profit}) \div \text{TIME TO ADJUST ELV PRICE} \tag{A.26}$$
Units: INR/Tonne-Month

'change in ELV formal price' and 'change in ELV informal price' gives the change in formal and informal market prices respectively. The mechanism of competition is as follows. At the beginning of the simulation, the formal and informal dismantlers offer the same price. In each period, they compare the price offered by the competitor, and if the competitor is offering the same price or a higher price, the dismantler increases the current price. There are two components of the price increase: 'formal/informal price difference from market' gives the difference of formal/informal price from the market price of ELV, and 'ELV price increment formal/informal' gives the increment (as a percentage of the current price) that the dismantler makes to surpass the competitor. The dismantlers increase the price from the current price only when they are generating profits.

$$\text{ELV price offered} = \text{Maximum}(\text{ELV Price Formal, ELV Price Informal}) \tag{A.27}$$
Units: INR/Tonne

'ELV price offered' gives the maximum price per tonne of ELV that can be offered by either the formal or informal dismantlers at a period.

$$\text{ELV market price} = \text{previous ELV market price} + \text{change in ELV market price} \tag{A.28}$$
Units: INR/Tonne

$$\text{previous ELV market price} = \text{DELAY FIXED (ELV market price, 1, INITIAL ELV price)} \tag{A.29}$$
Units: INR/Tonne

$$\text{change in ELV market price} = \text{ELV price offered} - \text{previous ELV market price} \tag{A.30}$$
Units: INR/Tonne

'ELV market price' gives the market price of ELV in each period. 'previous ELV market price' is the ELV market price in the previous period and 'change in ELV market price' gives the change in the market price of ELV in subsequent periods.

$$\text{effect of price on ELV supply} = \left(\frac{\text{ELV market price}}{\text{INITIAL ELV PRICE}}\right)^{\text{price sensitivity of ELV supply}} \tag{A.31}$$
Units: Dimensionless

$$\text{price sensitivity of ELV supply} = 1 \tag{A.32}$$
Units: Dimensionless

$$\text{ELV supply} = \text{INITIAL ELV SUPPLY} \times \text{effect of price on ELV supply} \tag{A.33}$$
Units: Tonnes/Month

'effect of price on ELV supply' gives the relative change in ELV supply for the relative change in the price of the ELV. 'price sensitivity of ELV supply' gives the elasticity of ELV supply to the changes in price, of which a higher value indicates more generation of ELVs for the change in ELV price and vice versa for a lower value. 'ELV supply' gives the amount of ELV generated with the current market price of ELV. This can be interpreted as the maximum amount of ELV the ELV owners are ready to sell to the dismantlers at the offered price. We adopt the method used in the commodity market model developed by Sterman (2010).

$$\text{INITIAL ELV SUPPLY} = 10000 \tag{A.34}$$
Units: Tonnes/Month

'INITIAL ELV SUPPLY' gives the amount of ELV at the beginning of the planning horizon. We assume the initial supply of ELV to be equal to the installed capacity of the formal dismantler.

$$\text{ELV available} = \text{Minimum}(\text{ELV Stock, ELV supply}) \tag{A.35}$$
Units: Tonnes/Month

'ELV available' refers to the maximum amount of ELV available for dismantling in the market. 'ELV supply' is the number of ELVs generated from the current market price of ELV. As the ELV is traded as a valuable resource in most emerging economies, the amount of ELV available for dismantling can be defined as a function of the market price. The minimization constraint for 'ELV available' ensures that the number of ELVs available will never exceed the maximum amount of ELVs generated from the existing vehicles.

The variables that are used for applying the rationing rules are described as follows.

$$\text{winner's dismantling quantity} = \begin{cases} \text{Minimum(ELV available, Informal Dismantling Capacity)}, \\ \qquad \text{if ELV Price Formal} < \text{ELV Price Informal} \\ \frac{\text{ELV available}}{2}, \\ \qquad \text{if ELV Price Formal = ELV Price Informal} \\ \text{Minimum(ELV available, FORMAL DISMANTLING CAPACITY)}, \\ \qquad \text{if ELV Price Formal} > \text{ELV Price Informal} \end{cases} \tag{A.36}$$
Units: Tonnes/Month

'winner's dismantling quantity' gives the ELV available for dismantling to the winner of the competition, the dismantler who offers the highest price for ELV. As shown in the Eq. (A.35), the dismantler who offers a higher price will get the majority of ELV available that is constrained by their capacity. When both the dismantlers offer the same price, both the dismantlers may get equal quantities.

$$\text{loser's dismantling quantity} = \text{Maximum}(\text{Minimum}(\text{ELV supply formal price, ELV supply informal price}) - \text{winner's dismantling quantity}, 0) \tag{A.37}$$
Units: Tonnes/Month

$$\text{ELV supply formal price} = \left(\frac{\text{ELV Price Formal}}{\text{INITIAL ELV PRICE}}\right)^{\text{price sensitivity of ELV supply}} \tag{A.38}$$
Units: Tonnes/ Month

$$\text{ELV supply informal price} = \left(\frac{\text{ELV Price Informal}}{\text{INITIAL ELV PRICE}}\right)^{\text{price sensitivity of ELV supply}} \tag{A.39}$$
Units: Tonnes/ Month

'loser's dismantling quantity' is the amount of ELV available for the dismantler who offers the lower price. At a lower price ELV owners may be willing to supply on a lesser quantity. So the dismantler who offers the lower price will be able to procure only a portion of leftover supply that is generated. We adapt the rule of Kreps and Scheinkman (1983) for calculating residual supply. 'ELV supply formal price' and 'ELV supply informal price' calculate the supply for the formal and informal ELV prices respectively (similar to calculating 'ELV supply'). The minimum price will generate a minimum residual quantity. The variable 'loser's dismantling quantity' also ensures a non-negative quantity.

The following equations calculate the quantities dismantled by the formal and informal dismantlers.

$$\text{formal ELV dismantling} = \begin{cases} \text{Minimum(winner's dismantling quantity, FORMAL DISMANTLING CAPACITY)}, \\ \qquad \text{if ELV Price Formal} > \text{ELV Price Informal} \\ \text{Minimum(FORMAL DISMANTLING CAPACITY,} \\ \text{Maximum(ELV available/2,ELV available - Informal Dismantling Capacity))}, \\ \qquad \text{if ELV Price Formal = ELV Price Informal} \\ \text{Minimum(loser's dismantling quantity, FORMAL DISMANTLING CAPACITY)}, \\ \qquad \text{if ELV Price Formal} < \text{ELV Price Informal} \end{cases} \tag{A.40}$$
Units: Tonnes/Month

$$\text{informal ELV dismantling} = \begin{cases} \text{Minimum(winner's dismantling quantity, Informal Dismantling Capacity)}, \\ \qquad \text{if ELV Price Inormal} > \text{ELV Price Formal} \\ \text{Minimum(Informal Dismantling Capacity,} \\ \text{Maximum(ELV available/2,ELV available - FORMAL DISMANTLING CAPACITY))}, \\ \qquad \text{if ELV Price Informal = ELV Price Formal} \\ \text{Minimum(loser's dismantling quantity, Informal Dismantling Capacity)}, \\ \qquad \text{if ELV Price Informal} < \text{ELV Price Formal} \end{cases} \tag{A.41}$$
Units: Tonnes/Month

"'formal ELV dismantling' and 'informal ELV dismantling' gives the amount of ELV dismantled by the formal and informal dismantlers per period. The dismantler, who is the winner, receives the ELV available initially and the leftover is received by the loser. In the case of both dismantlers offering the same price, they will dismantle the same amount of ELV, provided having enough capacity. Else the dismantler with higher capacity gets the opportunity to dismantle more than the competitor.

$$\text{total ELV dismantling} = \text{formal ELV dismantling} + \text{informal ELV dismantling} \tag{A.42}$$
Units: Tonnes/Month

$$\text{unsold ELV} = \text{ELV available} - \text{total ELV dismantling} \tag{A.43}$$
Units: Tonnes/Month

'total ELV dismantling' gives the combined quantity of ELVs dismantled by the formal and informal dismantlers. 'unsold ELVs' is the amount of ELVs available for dismantling but are not sold at a particular period. This may be due to the nonavailability of dismantling capacity or dismantlers not able to pay the price demanded by the owners of ELV. In this model, we assume that both the dismantlers dismantle the ELVs purchased in the same period without keeping any inventory. The ELVs that are unsold add to the stock of ELVs.

A3. Dismantlers' Revenue estimation

This section defines the variables that calculate the revenue generated by the dismantlers. Dismantlers generate their major revenue from the sale of steel scrap. Apart from that, the other revenue includes that from aluminum scrap, scrap plastics, rubber, etc. For ease of exposition, we assume the informal and formal dismantlers recover the same amount of materials from dismantling.

$$\text{RECOVERABLE STEEL SCRAP PER ELV} = 0.5625 \tag{A.44}$$
Units: Dimensionless

'RECOVERABLE STEEL SCRAP PER ELV' is the amount of steel scrap that can be recovered from one tonne of passenger vehicle scrap. Tripathi (2016) estimate the amount of steel scrap that can be recovered from a passenger vehicle as 0.45 tonnes, which we recalculate to per tonne of ELV scrap as 0.5625 tonnes.

$$\text{revenue from steel scrap} = \text{RECOVERABLE STEEL SCRAP PER ELV} \times \text{Steel Scrap Market Price} \tag{A.45}$$
Units: INR/Tonne

'revenue from steel scrap' gives the dismantler's revenue obtained by selling steel scrap from an ELV.

$$\text{OTHER REVENUE FROM ELV} = 1750 \tag{A.46}$$
Units: INR/Tonne

'OTHER REVENUE FROM ELV' gives the revenue obtained from the sale of other scrap material per tonne of ELV as estimated by Mohan Ram et al., 2015. This includes aluminum scrap, plastics, and other metal scraps in small quantities.

$$\text{revenue from ELV} = \text{revenue from steel scrap} + \text{OTHER REVENUE FROM ELV} \tag{A.47}$$
Units: INR/tonne

'revenue from ELV' gives the total revenue generated by a dismantler by dismantling one tonne of ELV.

A4. Formal dismantling

This section defines the variables defining the capacity, cost, and revenue aspects of the formal dismantler. As we consider the case of the Indian vehicle recycling industry, there is only one dismantler in the formal sector: 'Cero Recycling'. In this model, we assume a formal dismantler with similar attributes of "Cero Recycling'.

$$\text{FORMAL DISMANTLING CAPACITY} = 10000 \tag{A.48}$$
Units: Tonnes/ Month

'Cero Recycling'" has a capacity of about 0.1 - 0.15 million tonnes annually (Economic Times Auto, 2016). We also assume a similar capacity for the formal dismantler in our model. The dismantling capacity is taken as equal to the current rate of ELV generation. The capacity values are altered in later cases to analyze the impact of formal dismantler's capacity on the competition.

$$\text{formal total revenue from ELV} = \text{revenue from ELV} \times \text{formal ELV dismantling} \tag{A.49}$$
Units: INR/ Month

'formal total revenue from ELV' gives the total revenue obtained from dismantling ELV in a month.

The following equations calculate the total cost of formal dismantler.

$$\text{INITIAL INVESTMENT COST FORMAL} = 1200000000 \tag{A.50}$$
Units: INR

$$\text{ASSET LIFE} = 15 \tag{A.51}$$
Units: Years

$$\text{ASSET DISCOUNT RATE} = 0.15 \tag{A.52}$$
Units: Dimensionless

$$\text{asset cost formal} = \left(\frac{\text{initial investment cost} \times \text{ASSET DISCOUNT RATE}}{1 - (1 + \text{ASSET DISCOUNT RATE})^{-\text{ASSET LIFE}}} \right) \div 12 \tag{A.53}$$
Units: INR/ Month

$$\text{maintenance cost formal} = 0.10 \times \text{asset cost formal} \tag{A.54}$$
Units: INR/ Month

$$\text{LABOR COST FORMAL} = 528000 \tag{A.55}$$
Units: INR/ Month

$$\text{PROCESSING COST FORMAL} = 200 \tag{A.56}$$
Units: INR/ Month

$$\text{variable cost formal} = (\text{PROCESSING COST FORMAL} + \text{ELV Price Formal}) \times \text{formal ELV dismantling} \tag{A.57}$$
Units: INR/ Tonne

$$\text{total cost formal} = \text{variable cost formal} + \text{LABOR COST FORMAL} + \text{asset cost formal} + \text{maintenance cost formal} \tag{A.58}$$
Units: INR/ Tonne

$$\text{formal cost per tonne} = \frac{\text{total cost formal}}{\text{formal ELV dismantling}} \quad \text{Units: INR/Month-Tonne} \tag{A.59}$$

We consider the following costs are the main cost components for the formal ELV dismantler: asset cost, maintenance cost, labor cost, and variable costs involving the processing and purchase cost. Any other costs are assumed to be included while deciding the price of ELV. The costs are calculated using the technical cost model developed by Ferrão and Amaral (2006). The initial investment cost is assumed to the same as that of 'Cero Recycling' (Prasad, 2016). The cost of plant and equipment is calculated as equivalent annual costs as given by 'asset cost formal'. The life of plant and equipment is estimated as 15 years with a depreciation rate of 15% (Income Tax Department and Government of India, 2018). The maintenance cost is about 10% of the plant and equipment cost. The labor cost is calculated as the monthly salaries of employees required for permanent employees for a dismantling and shredding unit. The employee cost consists of salaries for three shifts of employees for dismantling and shredding. This includes 2 highly skilled workers and a manger for dismantling and 7 skilled workers, 2 highly skilled workers, and a maintenance manager for shredding. The salaries are approximated according to the prevailing salaries in the Indian vehicle industry. The processing cost includes the cost of power calculated with the prevailing power rates per on in India (India Briefing, 2015). '"total cost formal' gives the total cost incurred by the formal dismantler per month and 'formal cost per tonne' the total cost incurred by the formal dismantler per tonne of ELV per month.

$$\text{formal dismantler's profit} = \text{formal total revenue from ELV} - \text{total cost formal} \quad \text{Units: INR/ Tonne} \tag{A.60}$$

$$\text{formal profit per tonne} = \frac{\text{formal dismantler's profit}}{\text{formal ELV dismantling}} \quad \text{Units: INR/Month-Tonne} \tag{A.61}$$

'formal dismantler's profit' gives the total profit and 'formal profit per tonne' gives the profit made per tonne of ELV by the formal dismantler in each month.

A5. Informal dismantling

This section defines the variables defining the dynamics of informal dismantling. With the absence of official data regarding the number of ELV recyclers in India, the number and capacity of informal dismantlers are estimated from Central Pollution Control Board (CPCB), 2016, Akolkar et al., 2015, and Mohan Ram et al., 2015.

$$\text{total revenue informal} = \text{revenue from ELV} \times \text{informal ELV dismantling} \quad \text{Units: INR/ Tonne} \tag{A.62}$$

'total revenue informal' gives the revenue gives the total revenue generated by the informal dismantling industry per period.

$$\text{ELV PROCESSING COST INFORMAL} = 4375 \quad \text{Units: INR/tonne} \tag{A.63}$$

'ELV PROCESSING COST INFORMAL' gives the various costs involved in dismantling one tonne of ELV. This is predominantly the labor cost for manual dismantling and is estimated from the data from Mohan Ram et al., 2015. The nature of the cost function is linear as the laborers are paid per ELV dismantled.

$$\text{total dismantling cost informal} = \text{ELV PROCESSING COST INFORMAL} + \text{ELV Price Informal} \times \text{informal ELV dismantling} \quad \text{Units: INR/ tonne} \tag{A.64}$$

$$\text{informal cost per tonne} = \frac{\text{total dismantling cost informal}}{\text{informal ELV dismantling}} \quad \text{Units: INR/Month-Tonne} \tag{A.65}$$

'total dismantling cost informal' gives the total cost incurred by an informal dismantling industry comprising of the total purchase price and operating costs. 'informal cost per tonne' gives the cost incurred by the informal dismantler per tonne of the ELV dismantled.

$$\text{informal dismantling profit} = \text{total revenue informal - total dismantling cost informal} \quad \text{Units: INR/ tonne} \tag{A.66}$$

$$\text{informal profit per tonne} = \frac{\text{informal dismantling profit}}{\text{informal ELV dismantling}} \quad \text{Units: INR/Month-Tonne} \tag{A.67}$$

'informal dismantling profit' gives the total profit obtained by the informal dismantling industry. 'informal profit per tonne' gives the total profit made per tonne of ELV by informal dismantlers in a month.

$$\text{informal dismantler's profit} = \frac{\text{informal dismantling profit}}{\text{number of informal dismantlers}} \quad \text{Units: INR/ tonne} \tag{A.68}$$

'informal dismantler's profit' gives the total profit of an individual informal dismantler per period.

The informal dismantling market works similar to a perfectly competitive market with no barriers for entry and exit. New informal dismantlers enter when the current dismantlers able to generate profits and existing dismantlers exit when they are in loss. The following variables explain the entry and exit mechanism of informal dismantlers.

$$\text{decision to change informal capacity} = \begin{cases} 1, & \text{if informal dismantler's profit} > 0 \\ 0, & \text{otherwise} \end{cases} \tag{A.69}$$
Units: Dimensionless

$$\text{INFORMAL DISMANTLER'S CAPACITY} = 40 \tag{A.70}$$
Units: Tonnes/Dismantler

'INFORMAL DISMANTLER'S CAPACITY' gives the amount of ELVs an individual dismantler can dismantle in a month. The informal dismantlers are assumed to be homogeneous, all having the same capacity. By employing manual labor a particular dismantler dismantles a maximum of 40 tonnes of ELVs per month.

$$\text{informal dismantler entry or exit} = 1 \tag{A.71}$$
Units: Dismantler

'informal dismantler entry or exit' gives the number of informal dismantlers entering or exiting the market at a given period.

$$\text{change in informal capacity} = (\text{decision to change informal capacity} \times \text{INFORMAL DISMANTLER'S CAPACITY} \times \text{informal dismantler entry or exit}) \div \text{TIME TO ADJUST INFORMAL CAPACITY} \tag{A.72}$$
Units: Vehicles/Month

'change in informal capacity' gives the change in informal dismantling capacity due to the entry and exit of informal dismantlers with the varying profitability of the dismantling industry.

$$\text{TIME TO ADJUST INFORMAL CAPACITY} = 1 \tag{A.73}$$
Units: Month

'TIME TO ADJUST INFORMAL CAPACITY' gives the time for entry and exit of dismantlers. This time can be interpreted as the information delay in knowing about the profitability of dismantling.

$$\text{Informal Dismantling Capacity} = \text{INITIAL INFORMAL DISMANTLING CAPACITY} + \int_0^t (\text{change in informal capacity}) \times dt \tag{A.74}$$
Units: Vehicles/Month

'Informal Dismantling Capacity' is the number of ELVs that can be dismantled in each period by the informal dismantling sector. As this is a level variable that changes over time, we model it as a stock.

$$\text{INITIAL INFORMAL DISMANTLING CAPACITY} = 8000 \tag{A.75}$$
Units: Tonnes/Month

'INITIAL DISMANTLING CAPACITY' gives the total car dismantling capacity available in India in the current situation, which is estimated from the data from Akolkar et al., 2015 and Mohan Ram et al., 2015.

$$\text{number of informal dismantlers} = \frac{\text{Informal ELV Dismantling Capacity}}{\text{INFORMAL DISMANTLER'S CAPACITY}} \tag{A.76}$$
Units: Dismantler

The above equation calculates the number of informal dismantlers present in each period.

A6. Steel scrap price dynamics

This section explains the dynamics of steel scrap prices with the interaction of supply and demand.

$$\text{STEEL PRODUCTION GROWTH RATE} = 0.0058 \tag{A.77}$$
Units: Dimensionless

The government of India has set a target for crude steel production of 255 million tonnes by the financial year 2030-31, which accounts for more than double the current production (Ministry of Steel, 2017). In this model, we assume a uniform increase in steel production in all periods from the beginning of the simulation and estimate the value of 'STEEL PRODUCTION GROWTH RATE'.

$$\text{steel production increment} = \text{Steel Production} \times \text{STEEL PRODUCTION GROWTH RATE} \tag{A.78}$$
Units: Tonnes/Month

$$\text{INITIAL STEEL PRODUCTION} = 9000000 \tag{A.79}$$
Units: Tonnes/Month

$$\text{Steel Production} = \text{INITIAL STEEL PRODUCTION} + \int_0^t (\text{steel production increment}) \times dt \tag{A.80}$$
Units: Tonnes/Month

Crude steel production per time period is given by 'Steel Production' where 'INITIAL STEEL PRODUCTION' is the steel production at the beginning of the simulation. This data is based on annual reports of Ministry of Steel, Government of India, 2019. 'steel production increment' gives the increase in steel production.

$$\text{SCRAP USAGE RATE} = 0.3 \tag{A.81}$$
Units: Dimensionless

$$\text{steel scrap demand} = \text{Steel Production} \times \text{SCRAP USAGE RATE} \tag{A.82}$$
Units: Tonnes/Month

The amount of scrap usage in steel production is given by 'SCRAP USAGE RATE'. The usage of scrap in steel production is increasing in India and is estimated to reach around 30% by 2020-21 (Prithiani, 2017). In this model, we assume a constant scrap usage of 30%.

$$\text{ELV steel scrap supply} = \text{total ELV dismantling} \times \text{RECOVERABLE STEEL SCRAP PER ELV} \quad \text{(A.83)}$$

Units: Tonnes/Month

'ELV steel scrap supply' gives the amount of steel scrap generated from the ELV dismantling per period.

$$\text{previous ELV steel scrap supply} = \text{DELAY FIXED (ELV steel scrap supply, 1,ELV steel scrap supply)} \quad \text{(A.84)}$$

Units: Tonnes/Month

$$\text{relative change in ELV steel scrap supply} = \frac{\text{(ELV steel scrap supply - previous ELV steel scrap supply)}}{\text{previous ELV steel scrap supply}} \quad \text{(A.85)}$$

Units: Dimensionless

The dynamics in steel scrap supply is captured from the above equations, which in turn influences the change in the price of steel scrap. 'previous ELV steel scrap supply' gives the steel scrap supply from ELV in the previous period. 'relative change in ELV steel scrap supply' gives the percentage change in steel scrap supply between subsequent periods.

$$\text{supply sensitivity of steel scrap price} = \text{relative change in steel scrap supply} \quad \text{(A.86)}$$

Units: Dimensionless

'supply sensitivity of steel scrap price' gives the impact of supply changes on steel scrap price. The increase in the supply of steel scrap has a negative impact on the scrap price. Although the scrap supply from ELV forms only a part of total steel scrap supply, we assume the increase in ELV scrap supply to affect the scrap prices.

$$\text{demand sensitivity of steel scrap price} = \text{STEEL PRODUCTION GROWTH RATE} \quad \text{(A.87)}$$

Units: Dimensionless

As defined in Eq. (A.82), we assumed the scrap usage to be directly proportional to steel production, and thus increase in demand for steel scrap is given by 'STEEL PRODUCTION GROWTH RATE'. With the increase in demand 'demand sensitivity of steel scrap price' increases the steel scrap market price.

$$\text{change in steel scrap market price} = \text{Steel Scrap Market Price} \times \frac{\text{(demand sensitivity of steel scrap price - supply sensitivity of steel scrap price)}}{\text{TIME TO ADJUST STEEL SCRAP MARKET PRICE}} \quad \text{(A.88)}$$

Variable type: Flow
Units: INR/tonne

The flow variable 'change in steel scrap market price' changes in the market price of steel scrap relative to the change in supply and demand.

$$\text{TIME TO ADJUST STEEL SCRAP MARKET PRICE} = 1 \quad \text{(A.89)}$$

Units: Month

'TIME TO ADJUST STEEL SCRAP MARKET PRICE' gives the first-order delay (if any) in adjusting the market scrap prices.

$$\text{INITIAL STEEL SCRAP MARKET PRICE} = 24800 \quad \text{(A.90)}$$

Units: INR/tonne

'INITIAL STEEL SCRAP MARKET PRICE' is the existing price of scrap at the beginning of the simulation and is obtained from crisilresearch.com.

$$\text{Steel Scrap Market Price} = \text{INITIAL STEEL SCRAP MARKET PRICE} + \int_0^t (\text{change in steel scrap market price}) \times dt \quad \text{(A.91)}$$

Units: INR/tonne

'Steel Scrap Market Price' gives the market price of steel scrap in each period.

The basic unit of time is taken as a month. The 'TIME STEP' is taken as 1 (one month).

References

Albertson, K., Aylen, J., 1996. Modelling the great lakes freeze: forecasting and seasonality in the market for ferrous scrap. Int. J. Forecast. 12, 345–359.

Amaral, J., Ferrão, P., Rosas, C., 2006. Is recycling technology innovation a major driver for technology shift in the automobile industry under an EU context? Int. J. Technol. Policy Manage. 6, 385–398.

Arora, N., Bakshi, S.K., Bhattacharjya, S., 2019. Framework for sustainable management of end-of-life vehicles management in India. J. Mater. Cycles Waste Manage. 21, 79–97. doi:10.1007/s10163-018-0771-0.

Azmi, M., Tokai, A., 2017. Electric vehicle and end-of-life vehicle estimation in Malaysia 2040. Environ. Syst. Decisi. 37, 451–464. doi:10.1007/s10669-017-9647-4.

Bandivadekar, A.P., Kumar, V., Gunter, K.L., Sutherland, J.W., 2004. A model for material flows and economic exchanges within the US automotive life cycle chain. J. Manuf. Syst. 23, 22–29. doi:10.1016/S0278-6125(04)80004-9.

Barlas, Y., 1996. Formal aspects of model validity and validation in system dynamics. System Dynamics Review 12, 183–210. Doi:10.1002/(sici)1099-1727(199623)12:3<183::aid-sdr103>3.0.co;2-4

Brady, M.P., 2009. Advertising effectiveness and spillover: simulating strategic interaction using advertising. Syst. Dyn. Rev. 25, 281–307. doi:10.1002/sdr.426.

Prithiani, R. (2017). Evolving role of scrap in India. https://dokumen.tips/documents/evolving-role-of-scrap-in-india-mraiorgin-prithiani-crisilpdf-evolving.html. (Accessed December 11, 2017).

Akolkar, A.B., Sharma, M., Puri, M., Chaturvedi, B., Mehra, G., Bharadwaj, S., Mutz, G., Arora, R., & Saluja, M. S. (2015). Analysis of end of life vehicles (ELVs) sector in India. Technical Report. Central Pollution Control Board and Chintan Environmental Research and Action Group and Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, New Delhi. URL: https://www.chintan-india.org/sites/default/files/2019-09/ELV%20Report%202015%20Final.pdf

Central Pollution Control Board (CPCB), Government of India (November 2016). Guidelines for environmentally sound management of end-of-life vehicles (ELVs). Technical Report. Central Pollution Control Board, India.

cerorecycling.com (2020). https://cerorecycling.com/. (Accessed April 23, 2020).

Chen, Z., Chen, D., Wang, T., Hu, S., 2015. Policies on end-of-life passenger cars in china: dynamic modeling and cost-benefit analysis. J. Clean Prod. 108, 1140–1148. doi:10.1016/j.jclepro.2015.07.093.

Chesterton, A. (2018). How many cars are there in the world? https://www.carsguide.com.au/car-advice/how-many-cars-are-there-in-the-world-70629. (Accessed November 20, 2018).

Cruz-Rivera, R., Ertel, J., 2009. Reverse logistics network design for the collection of end-of-life vehicles in Mexico. Eur. J. Oper. Res. 196, 930–939. doi:10.1155/2010/649028.

data.gov.in (2017). Total number of registered motor vehicles in india from 1951 to 2015. https://data.gov.in/search/site?query=Total+number+of+registered+motor+vehicles+in+india+from+1951+to+2015. (Accessed March 01, 2017).

Economic Times Auto (2016). Mahindra intertrade partners MSTC to set up india's first auto shredding facility. http://auto.economictimes.indiatimes.com/news/industry/mahindra-intertrade-partners-mstc-to-set-up-indias/-first-auto-shredding-facility/52025721. (Accessed May 1, 2016).

Economic Times Auto (2019). Maruti suzuki partners with toyota tsusho for vehicle dismantling and recycling. https://auto.economictimes.indiatimes.com/news/industry/maruti-suzuki-partners-with-toyota-tsusho-for-vehicle/-dismantling-and-recycling/71935051. (Accessed November 7, 2019).

El Halabi, E., Doolan, M., 2013. Causal Loops in Automotive Recycling. In: Proceedings of the 56th annual meeting of the ISSS-2012, san jose, CA, USA.

Farel, R., Yannou, B., Ghaffari, A., Leroy, Y., 2013. A cost and benefit analysis of future end-of-life vehicle glazing recycling in france: a systematic approach. Resour. Conserv. Recycl. 74, 54–65. doi:10.1016/j.resconrec.2013.02.013.

Ferrão, P., Amaral, J., 2006. Assessing the economics of auto recycling activities in relation to european union directive on end of life vehicles. Technol. Forecast. Soc. Change 73, 277–289. doi:10.1016/j.techfore.2004.03.010.

Hedayati, M., 2016. System Model for Sustainable End-of-Life Vehicle Treatment in the Australian Context. RMIT University Ph.D. thesis..

Hu, S., Wen, Z., 2015. Why does the informal sector of end-of-life vehicle treatment thrive? a case study of china and lessons for developing countries in motorization process. Resour. Conserv. Recycl. 95, 91–99. doi:10.1016/j.resconrec.2014.12.003.

Hornig, S., Stadler, M., 2000. No information sharing in oligopoly: The case of price competition with cost uncertainty. Technical Report. Tübinger Diskussionsbeiträge, 194. University of Tübingen, School of Business and Economics https://www.econstor.eu/bitstream/10419/47564/1/57562065X.pdf.

Income Tax Department, Government of India, (2018). Rates of depreciation. https://www.incometaxindia.gov.in/_layouts/15/dit/mobile/viewer.aspx?path=https://www.incometaxindia.gov.in/charts%20%20tables/depreciation%20rates.htm&k=&IsDlg=0. (Accessed October 12, 2018).

India Briefing (2015). Industrial power rates in India. https://www.india-briefing.com/news/industrial-power-rates-india-11062.html/. (Accessed October 12, 2018).

Inghels, D., Dullaert, W., Raa, B., Walther, G., 2016. Influence of composition, amount and life span of passenger cars on end-of-life vehicles waste in Belgium: a system dynamics approach. Transport. Res. Part A 91, 80–104. doi:10.1016/j.tra.2016.06.005.

Karagoz, S., Aydin, N., Simic, V., 2019. End-of-life vehicle management: a comprehensive review. J. Mater. Cycle. Waste Manage. 1–27. doi:10.1007/s10163-019-00945-y.

Kreps, D.M., et al., 1990. A Course in Microeconomic Theory. Princeton university press.

Kreps, D.M., Scheinkman, J.A., 1983. Quantity precommitment and bertrand competition yield cournot outcomes. Bell J. Econ. 326–337.

Kumar, S., Yamaoka, T., 2007. System dynamics study of the japanese automotive industry closed loop supply chain. J. Manufact. Technol. Manage. 18, 115–138. doi:10.1108/17410380710722854.

Li, Y., Fujikawa, K., Wang, J., Li, X., Ju, Y., Chen, C., 2020. The potential and trend of end-of-life passenger vehicles recycling in china. Sustainability 12(4), 1455. doi:10.3390/su12041455.

Ministry of Steel, Government of India, (2017). National steel policy. http://steel.gov.in/national-steel-policy-nsp-2017. (Accessed November 15, 2017).

Ministry of Road Transport, Highways, Government of India, 2016. https://morth.nic.in/sites/default/files/circulars_document/Concept_Note_on_Voluntary_Vehicle_Fleet_Modernization_Programme.pdf.

Mohamad-Ali, N., Ghazilla, R., Abdul-Rashid, S., Sakundarini, N., Ahmad-Yazid, A., Stephenie, L., 2018. End-of-life vehicle recovery factors: Malaysian stakeholders' views and future research needs. Sustain. Develop. 26, 713–725. doi:10.1002/sd.1741.

Mohan, T.V.K., Amit, R.K., 2020. Dismantlers' Dilemma in end-of-life vehicle recycling markets: a system dynamics model. Ann. Oper. Res. 290, 591–619. doi:10.1007/s10479-018-2930-z.

Mohan Ram, N.S., 2018. Recycling End of Life Vehicles: With Special Focus on India and Developing Nations. Productivity and Quality Publishing Pvt. Ltd..

Ministry of Steel, Government of India, (2019). Annual reports (from 2003to 04 to 2018-19). https://steel.gov.in/annual-reports. (Accessed November 30, 2019).

Prasad, G. C. (2016). MSTC-Mahindra auto shredding JV will boost manufacturing: Chaudhary birender singh. http://www.livemint.com/Industry/oqDeHqnbwu6b3qElogncAO/MSTCMahindra-auto-shreddingJV-will-boost-manufacturing-Ch.html. (Accessed August 10, 2016).

Press Trust of India, (2020). Govt set to introduce vehicle scrappage policy to boost india's auto manufacturing: Gadkari. https://auto.economictimes.indiatimes.com/news/industry/govt-set-to-introduce-vehicle-scrappage-policy-to-boost-indias-auto-/manufacturing-gadkari/75875072. (Accessed May 29, 2020).

Mohan Ram, Adhikari, B., Sugmar, S., 2015. Development of scientific recycling of end of life automobiles in India and the role of research and development. Technical Report. Indian National Academy of Engineering https://www.inae.in/core/assets/fortuna-child/img/Report%20on%20Automotive%20Recycling.pdf.

Qu, X., Williams, J.A.S., 2008. An analytical model for reverse automotive production planning and pricing. Eur. J. Oper. Res. 190, 756–767. doi:10.1016/j.ejor.2007.06.041.

Rahmandad, H., Sibdari, S., 2012. Joint pricing and openness decisions in software markets with reinforcing loops. Syst. Dyn. Rev. 28, 209–229. doi:10.1002/sdr.1473.

Rahmandad, H., Spiteri, R., 2015. Analytical Methods for Dynamic Modelers. In: chapter 12 modeling competing actors using differential games. MIT Press, p. 373.

Rosa, P., Terzi, S., 2018. Improving end of life vehicle's management practices: an economic assessment through system dynamics. J. Clean. Prod. 184, 520–536. doi:10.1016/j.jclepro.2018.02.264.

Sharma, L., Pandey, S., 2020. Recovery of resources from end-of-life passenger cars in the informal sector in india. Sustainable Production and Consumption 24, 1–11. doi:10.1016/j.spc.2020.06.005. In press

Sice, P., Mosekilde, E., Moscardini, A., Lawler, K., French, I., 2000. Using system dynamics to analyse interactions in duopoly competition. System Dynamics Review: The Journal of the System Dynamics Society 16, 113–133. Doi:10.1002/1099-1727(200022)16:2<113::AID-SDR189>3.0.CO;2-G

Simic, V., 2015. Fuzzy risk explicit interval linear programming model for end-of-life vehicle recycling planning in the EU. Waste Manage. 35, 265–282. doi:10.1016/j.wasman.2014.09.013.

Simic, V., 2016a. End-of-life vehicles allocation management under multiple uncertainties: an interval-parameter two-stage stochastic full-infinite programming approach. Resour. Conserv. Recycl. 114, 1–17. doi:10.1016/j.resconrec.2016.06.019.

Simic, V., 2016b. A multi-stage interval-stochastic programming model for planning end-of-life vehicles allocation. J. Clean. Prod. 115, 366–381. doi:10.1016/j.jclepro.2015.11.102.

Simic, V., Dimitrijevic, B., 2012. Production planning for vehicle recycling factories in the EU legislative and global business environments. Resour. Conserv. Recycl. 60, 78–88. doi:10.1016/j.resconrec.2011.11.012.

Simic, V., Dimitrijevic, B., 2013. Risk explicit interval linear programming model for long-term planning of vehicle recycling in the EU legislative context under uncertainty. Resour. Conserv. Recycl. 73, 197–210. doi:10.1016/j.resconrec.2013.02.012.

crisilresearch.com (2019). Data and statistics: Prices-scrap. https://www.crisilresearch.com/. (Accessed September 20, 2019).

Society of Indian Automobile Manufacturers, (2020). Automobile domestic sales trends. http://www.siamindia.com/statistics.aspx?mpgid=8&pgidtrail=14. (Accessed April 24, 2020).

Sterman, J.D., 2010. Business Dynamics: Systems Thinking and Modeling for a Complex World. McGraw Hill Education (India) Private Limited.

Steuer, B., Ramusch, R., Salhofer, S., et al., 2018. Is there a future for the informal recycling sector in urban China? Detritus 189. doi:10.31025/2611-4135/2018.13725.

tatasteel.com (2019). Tata to set up first steel scrap recycling plant. https://www.tatasteel.com/media/newsroom/in-the-news/2019/tata-to-set-up-first-steel-scrap-recycling-plant/. (Accesses May 29,2020).
Tian, F., Sošić, G., Debo, L., 2020. Stable recycling networks under the extended producer responsibility. Eur. J. Oper. Res. 287, 989–1002. doi:10.1016/j.ejor.2020.05.002.
toyota global.com (2014). Vehicle recycling toyota. http://www.toyota-global.com/sustainability/report/vehicle_recycling/pdf/vr_all.pdf. (Accessed June 23, 2016).
Tripathi, S. K. (2016). Automotive shredding in India - The plan and policies. Presented at the Scrap Recycling Conference: Emerging Markets, New Delhi, India.
Vidovic, M., Dimitrijevic, B., Ratkovic, B., Simic, V., 2011. A novel covering approach to positioning ELV collection points. Resour. Conserv. Recycl. 57, 1–9. doi:10.1016/j.resconrec.2011.09.013.
Wang, Y., Chang, X., Chen, Z., Zhong, Y., Fan, T., 2014. Impact of subsidy policies on recycling and remanufacturing using system dynamics methodology: a case of auto parts in china. J. Clean. Prod. 74, 161–171. doi:10.1016/j.jclepro.2014.03.023.
Williams, J.A.S., Wongweragiat, S., Qu, X., McGlinch, J.B., Bonawi-tan, W., Choi, J.K., Schiff, J., 2006. An automotive bulk recycling planning model. Eur. J. Oper. Res. 177, 969–981. doi:10.1016/j.ejor.2006.01.031.
Zamudio-Ramirez, P., 1996. Economics of automobile recycling. Massachusetts Institute of Technology Master's thesis.