Improving end of life vehicle's management practices: An economic assessment through system dynamics

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Abstract

End-of-Life Vehicles (ELVs), together with Waste from Electrical and Electronic Equipments (WEEE), are one of the most valuable sources of secondary raw materials. Their reuse for producing new goods is a well-known topic in the literature. However, End-of-Life (EoL) strategies implemented by companies remained the same since the last century, completely based on materials market prices. Progressively, this way of doing exposed the entire ELV recovery chain to a series of unwanted market risks. The purpose of this paper is proposing an alternative way to cope with the material's mix evolution in cars through the recovery of automotive electronic components. By applying an already existing model based on the System Dynamics (SD) methodology to the Italian context, a real time comparison of several configurations (scenarios) of the national ELV recovery chain has been implemented. Results quantified the expected impact on profits of both dismantlers and shredders in about 9 and 7.6 billion euros within fifty years. This way, dismantlers should lead the new recovery process, considering the highest increase in profits. However, the level of risk related with this option has been hypothesised as higher than a scenario with shredders leading the business.

Keywords: End of Life Vehicles; System Dynamics; Economic Assessment; Italian context.

Nomenclature			
ABC	Activity Based Costing	GDP	Gross Domestic Product
ASR	Automotive Shredder Residue	GF	Gompertz Function
CBA	Cost-Benefit Analysis	LP	Linear Programming
D-S	Decision-Support	MCDA	Multi-Criteria Decision Approach
DFD	Design for Disassembly	MI-LP	Multi-Integer Linear Programming
ECU	Electronic Control Unit	NLP	Non-Linear Programming
EGT	Evolutionary Game Theory	PCB	Printed Circuit Board
ELV	End-of-Life Vehicle	S-CBA	Social Cost-Benefit Analysis
EoL	End of Life	SA	Scenario Analysis
FL	Fuzzy Logic	SD	System Dynamics
GA-NN	Genetic Algorithm Neural Network	WEEE	Waste from Electrical and Electronic Equipments

1. Introduction

End of life vehicles (ELVs) are re-known by the experts as one of the main sources – together with waste from electrical and electronic equipment (WEEE) – of secondary raw materials. Considering the most updated estimates, the only Europe generates yearly from 7 to 14 million tons of ELVs ((Eurostat, 2015); (Andersen et al., 2008)), with an annual growth rate from 2% to 8% ((Passarini et al., 2012); (Vermeulen et al., 2011)). Almost 70% of these amounts are directly reused by companies to produce new goods. Even if the ELV recovery chain is an already established industry in Europe, its management strategies remained the same since many decades, completely based on raw materials market prices (especially related to ferrous metals) ((Kumar and Yamaoka, 2007); (Amaral et al., 2006)). In the last years, this way of doing exposed national ELV recovery chains to several market risks, like unpredictable fluctuations of raw materials market prices, uncontrolled illegal transfer of vehicles among nations and the unavoidable evolution of ELVs' materials mix ((Jain et al., 2015)). Trying to control – and partially limit – the company's exposition to previous (and other) risks, experts in product EoL management proposed several interesting works supporting actors in predicting, assessing and optimizing different aspects related with ELV recovery chains. The following sub-sections will compare these works, by identifying their type and focus, trying to clearly show what are the current lacks in literature.

1.1. Type of decision-support methods supporting ELV recovery chains

Depending on the model type, a wide range of decision-support methods were applied, but System Dynamics (SD) seems to be the most common one. All of these information are summarized in **Table 1**.

Table 1. Macro topic, model type and decision-support method of current literature works

	Model type				
Macro topic	Predictive	Assessment	Optimization	**D-S method**	**Reference**
Resource management	x			SA	(Alonso et al., 2012)
Environmental policies		x		SD	(Amaral et al., 2006)
Future ELV flows	x			GF	(Andersen et al., 2008)
EoL strategies		x		SD	(Asif et al., 2010)
Environmental policies		x		SD	(Che et al., 2011)
Environmental policies		x		SD	(Chen et al., 2015)

Economic sustainability		x		ABC	(Coates and Rahimifard, 2008)
Environmental policies		x		MCDA	(Cucchiella et al., 2017)
Reverse logistic chains			x	MI-LP	(Demirel et al., 2016)
Operational challenges		x		SD	(El Halabi et al., 2012)
Operational challenges		x		SD	(El Halabi and Doolan, 2013a)
Operational challenges		x		SD	(El Halabi and Doolan, 2013b)
Reverse logistic chains			x	LP	(Farel et al., 2013a)
Economic sustainability			x	SD	(Farel et al., 2013b)
Resource management		x		LP	(Garcia et al., 2015)
Environmental policies		x		CBA	(GHK and Bio Intelligence Service, 2006)
Reverse logistic chains		x		SD	(Gu and Gao, 2011)
Future ELV flows	x			GF	(Hu and Kurasaka, 2013)
Social sustainability		x		S-CBA	(Hu and Wen, 2017)
Future ELV flows	x			SD	(Inghels et al., 2016)
Economic sustainability		x		FL	(Keivanpour et al., 2013)
EoL strategies		x		EGT	(Keivanpour et al., 2017)
Economic sustainability		x		SD	(Kibira and Jain, 2011)
Environmental policies		x		SD	(Kumar and Yamaoka, 2007)
Resource management			x	FL	(Mayyas et al., 2016)
Reverse logistic chains			x	MCDA	(Mergias et al., 2007)
Environmental policies		x		SD	(Mohamad-Ali et al., 2017)
Reverse logistic chains			x	NLP	(Qu and Williams, 2008)
Reverse logistic chains			x	LP	(Simic, 2015)
Resource management		x		SD	(Soo et al., 2015)
Future ELV flows	x			GA-NN	(Tian et al., 2013)
Reverse logistic chains			x	SD	(Vlachos et al., 2007)
Environmental policies		x		SD	(Wang et al., 2014)
Economic sustainability		x		SD	(Zamudio-Ramirez, 1996)
Reverse logistic chains			x	MCDA	(Zhou et al., 2016)

1.2. Focus of decision-support methods supporting ELV recovery chains

Even if several contributions can be found on these topics, new strategies on how to cope with the technological evolution of ELVs are still lacking in the scientific literature, as underlined in other works (e.g. (Rosa and Terzi, 2016); (Lehr et al., 2013)). Generally, all of the contributions were either focused on a specific issue affecting the current industrial context (e.g. the economic performance or the influence of other actors on decisions taken by a single player) or validated in a real industrial context. However, innovative ways of doing business able, at the same time, to improve national ELV recovery chains' economic performances were rarely proposed. Only few works (e.g. (Coates and Rahimifard, 2008); (Kibira and Jain, 2011); (Farel et al., 2013b)) adopted this logic, like reported in the following **Table 2**.

Table 2. Features of current literature works

Reference	Focused on economic performance	Focused on multi-actor relations	Validated in a real industrial context	Proposing innovative businesses
(Alonso et al., 2012)				
(Amaral et al., 2006)	x	x	x	
(Andersen et al., 2008)				
(Asif et al., 2010)			x	
(Che et al., 2011)			x	
(Chen et al., 2015)	x			
(Coates and Rahimifard, 2008)	**x**	**x**	**x**	**x**
(Cucchiella et al., 2017)				
(Demirel et al., 2016)		x	x	
(El Halabi et al., 2012)	x			
(El Halabi and Doolan, 2013a)	x		x	
(El Halabi and Doolan, 2013b)	x	x	x	
(Farel et al., 2013a)	x		x	
(Farel et al., 2013b)	**x**	**x**	**x**	**x**
(Garcia et al., 2015)			x	
(GHK and Bio Intelligence Service, 2006)	x			
(Gu and Gao, 2011)		x		
(Hu and Kurasaka, 2013)			x	
(Hu and Wen, 2017)				
(Inghels et al., 2016)		x	x	
(Keivanpour et al., 2013)	x			
(Keivanpour et al., 2017)		x	x	
(Kibira and Jain, 2011)	**x**	**x**	**x**	**x**
(Kumar and Yamaoka, 2007)	x	x	x	
(Mayyas et al., 2016)				
(Mergias et al., 2007)			x	
(Mohamad-Ali et al., 2017)		x		
(Qu and Williams, 2008)		x	x	
(Simic, 2015)		x		
(Soo et al., 2015)				
(Tian et al., 2013)				
(Vlachos et al., 2007)		x		
(Wang et al., 2014)	x		x	
(Zamudio-Ramirez, 1996)	x	x	x	
(Zhou et al., 2016)				

However, also these three papers do not consider an important element embedded in modern cars that was subjected to a strong evolution in the last decades, like electronic components. Given all of these elements, the intent of this paper is threefold. From one side, there is the need to make European companies involved in ELV recovery chains aware about the economic potential of alternative – and more sustainable – business strategies (e.g. related with the recovery of automotive electronics) through a dedicated decision-support tool (e.g. based on the SD approach). From a second side, the decision-support tool must assess multi-actor interactions and their influence on the overall economic performance of the entire ELV recovery chain. From a third side, the decision-support tool

must be tested and validated in a real industrial context (e.g. the Italian one). This way, important findings coming from this work could help governmental and industrial actors with the comparison of results coming from similar types of simulation models available in literature, so better understanding the cause of lost opportunities, trying to refine both current European ELV and WEEE directives accordingly.
The paper is organized as follows. Section 2 presents a literature review about the scrap automotive electronics management and the SD methodology application to the ELV management sector. Section 3 describes the SD model adopted within this study. Section 4 presents an analysis of the Italian context taken into account within this work. Section 5 discusses the results coming from the application of the SD model to the current Italian context and their comparison with potential performances offered by the recovery of scrap automotive electronics. Section 6 makes some concluding remarks and future perspectives.

2. Research framework

In general terms, ELVs are those vehicles reaching the end of their useful life because of either an extreme accident or obsolescence (e.g. (Vermeulen et al., 2011)). The first ones are commonly called premature ELVs. The second ones are commonly called natural ELVs. However, whatever their origin, they end all to be managed by the same reverse logistic chain, being it legal or not. Within the whole paper only the official ELV recovery chain will be considered. In the following sub-sections, a generic description of the ELV recovery chain logic, the management of automotive electronic components and the relation between SD models and ELV management will be presented.

2.1. A generic ELV recovery chain

A typical ELV recovery process is reported in **Figure 1**, under the form of an IDEF0 model. ELVs are collected and deleted from the public register, and the main hazardous components (e.g., batteries, fuel, and filters) are removed. Subsequently, most of the valuable parts (e.g., catalyst, engine, and some mechatronic components) are disassembled (if in good conditions and with a market request), and reused as spare parts in secondary markets. The car hulk is then crushed and fragmented into small scraps. Subsequently, the scraps are separated by exploiting their physical characteristics (e.g., density, weight, and magnetism) to obtain uniform groups of materials. In general, ferrous metals (about 65% of the average mass) ((Hu and Wen, 2015)) are directly reintroduced into the automotive supply chain (as input material for foundries). Non-metals (generally named Automotive Shredder Residue (ASR) and constituting about the 25% of the average mass) are currently landfilled or used as fuel for energy generation ((Ni and Chen, 2014)). Finally, non-ferrous metals (about the 5% of the average mass) – depending on setup parameters of the specific treatment plant – becomes impurities of both the ferrous and non-metal fractions.

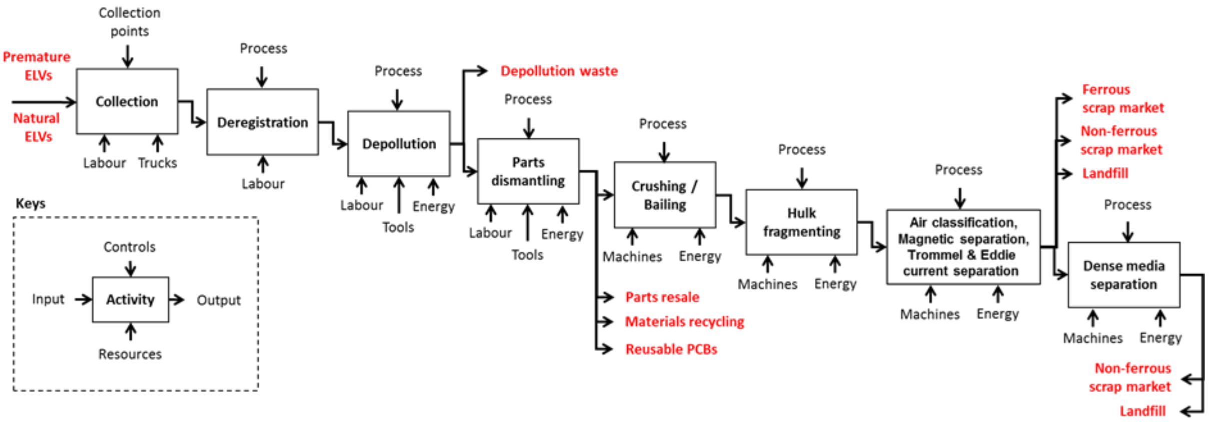

Figure 1. The current recovery process of ELVs – (Adapted from (Vermeulen et al., 2011))

However, the entire recovery process is based on technologies developed more than fifty years ago. The experts proposed many innovative procedures during the last decades ((Tian et al., 2015)). However, the focus is still on alternative – or better – ways to increase recovery percentages of the car hulk (or the remaining mass of a car after depollution and dismantling) that is currently incinerated or landfilled – the so called ASR ((Zorpas and Inglezakis, 2012); (Vermeulen et al., 2011)).

2.2. Scrap automotive electronics management

Electronic Control Units (ECUs) – generally constituted by a Printed Circuit Board (PCB) sealed within a metal case - are among the most valuable mechatronic devices embedded in modern vehicles. They are able to perform the reading of signals coming from sensors embedded in a car, and control the behaviour of many sub-systems, as engine, air conditioning and infotainment systems and safety devices ((Wang and Chen, 2011)). The current amount of electronic components present in cars is impressive, both in numbers and in impact on costs. A modern medium-sized car can embed up to 15 electronic systems on average ((Kripli et al., 2010)) and luxury cars can reach up to 50 among microcomputers and electronic components ((Freiberger et al., 2012)). In terms of production costs, a statistic of the Bayerische Motoren Werke Corporation described that these systems can account for more than 30% of total vehicle cost, reaching more than 50% in luxury cars ((Wang and Chen, 2013)). More precise data on the economic value embedded in scrap automotive electronics are also present in literature ((Cucchiella et al., 2016a)). For example, referring to 2015 data, expected annual generated volumes in the only Europe were estimated in 186.5 kilo tons, with an expected Net Present Value (NPV) going from a minimum of 891 million € up to a maximum of 8,4 billion €. However, current ELV directives (based on weighting principles) seems to do not adequately take into account the management of these types of e-wastes ((Rosa and Terzi, 2016)). Hence, there are no benefits for the actors involved in the automotive reverse logistic chain to invest in dedicated recovery centres ((Cucchiella et al., 2016b)).

2.3. SD models and ELV management

The use of SD models to assess different features related with the ELV recovery chain is not a new idea. The scientific literature presents several works going into this direction, under the form of both journal and conference papers. Focusing the attention on SD-based decision-support tools focused on ELV management, it is possible to identify the following **Table 3**, underlining the current literature gaps in this research domain. In general terms, **Table 3** allows to divide the selected papers into four relevant categories.

Table 3. Features of current SD-based decision-support tools dedicated to ELV management

Reference	Focused on economic performance	Focused on multi-actor relations	Validated in a real industrial context	Proposing innovative businesses
(Amaral et al., 2006)	x	x	x	
(Asif et al., 2010)			x	
(Che et al., 2011)			x	
(Chen et al., 2015)	x			
(El Halabi et al., 2012)	x			
(El Halabi and Doolan, 2013a)	x		x	
(El Halabi and Doolan, 2013b)	x	x	x	
(Farel et al., 2013b)	x	x	x	x
(Gu and Gao, 2011)		x		
(Inghels et al., 2016)		x	x	
(Kibira and Jain, 2011)	x	x	x	x
(Kumar and Yamaoka, 2007)	x	x	x	
(Mohamad-Ali et al., 2017)		x		
(Soo et al., 2015)				
(Vlachos et al., 2007)		x		
(Wang et al., 2014)	x		x	
(Zamudio-Ramirez, 1996)	x	x	x	

First of all, there is a group of papers who, even if presenting a SD-based decision-support tool, they do not have an economic perspective. This is the case of seven works out of seventeen ((Asif et al., 2010); (Che et al., 2011); (Gu and Gao, 2011); (Inghels et al., 2016); (Mohamad-Ali et al., 2017); (Soo et al., 2015); (Vlachos et al., 2007)). More into detail, the work of Asif et al. (2010) is focused on the assessment, through a SD model, of a new concept – based on remanufacturing principles – to be used in the product realization process for ensuring optimum useable life of products (or parts of them) and enabling multiple lifecycles. The paper of Che et al. (2011) is completely dedicated to the evaluation of cooperation practices in terms of ELV management in the Asian far-east region. In the same year, Gu and Gao (2011) assesses the impact of Radio Frequency Identification Device (RFID) on reverse logistics' general performances. Inghels et al. (2016) assesses the influence of material composition, amount and lifespan of passenger cars on ELV flows to draw some perspectives on future wastes in Belgium. Mohamad-Ali et al. (2017) exploit the SD methodology to assess Design for Recovery (DfR) rules impact on the Malaysian ELV context. Soo et al. (2015) present a dynamic hypothesis illustrating the time effect on life cycle analysis of a car for investigating challenges associated to the materials recovery efficiency. Finally, Vlachos et al. (2007) exploit the SD methodology to implement a capacity planning model of remanufacturing plants.

A second group is composed by papers with a clear economic perspective, but either focused on a single actor of the ELV supply chain or without any real validation in the industrial context. This is the case of four works out of seventeen ((Chen et al., 2015); (El Halabi et al., 2012); (El Halabi and Doolan, 2013a); (Wang et al., 2014)). More into detail, the work of Chen et al. (2015) propose a dynamic modelling and cost-benefit analysis investigating how polices, including government sub-

sidies, a value-added tax and a deposit-refund system, may affect the recycling of end-of-life passenger cars in China. The paper of El Halabi et al. (2012) presents an approach to extract factors and causal influences from interview data with stakeholders of the Australian automotive recycling system during the SD model conceptualisation stage. Subsequently, El Halabi et al. (2013a) presents a discussion of the causal loops and scenarios identified from interview data and field observations around the dynamics of ELVs. Finally, Wang et al. (2014) explored the impact of subsidy policies on the development of the recycling and remanufacturing industry in China using the system dynamics methodology and by simulating the Chinese auto parts industry.
A third group is constituted by papers completely focused on economic performances of the ELV recovery chain, with a multi-actor perspective and validated in a real industrial context. This is the case of four works out of seventeen ((Amaral et al., 2006); (El Halabi and Doolan, 2013b); (Kumar and Yamaoka, 2007); (Zamudio-Ramirez, 1996)). More into detail, the work of Amaral et al. (2006) makes use of a system dynamics model, applied to the Portuguese ELV-processing infrastructure, evaluating how current practices under different recycling strategies depend on both the recycled materials market and the car's composition. Instead, El Halabi et al (2013b) tried to explore the root causes of the operational challenges facing the automotive recycling business. (Kumar and Yamaoka, 2007) examined different EoL strategies and applied them to the Japanese automotive sector. However, the focus was on the effect of national policies (in terms of import and export of cars) on the national ELV recovery chain. Finally, the most significant example is given by the work of Zamudio-Ramirez (1996). Even if under the form of a thesis (never published), this work assessed the economic performance of the North American automotive recycling chain, going to evaluate the effects of different policies regarding the materials composition of cars on the final profits of both dismantlers and shredders. From a purely economic view, this is the only example of a SD model focused on the comprehension of the set of internal drivers influencing transactions among all the involved actors and their reciprocal influence on others economic performances. Furthermore, this work was also the first one (in chronological terms) completely based on the SD approach.
A fourth – and final – group is composed by papers who, in addition to all of the features characterizing the third group, offers also some new perspectives in terms of innovative ways of doing business within the ELV recovery chain. This is the case of only two works out of seventeen ((Farel et al., 2013b); (Kibira and Jain, 2011)). More into detail, the paper of Kibira and Jain (2011) evaluated the impact of hybrid and electric vehicles on dismantler and shredder profits. The results confirm that a technological development for the recovery of alternative materials than ferrous metals is needed to counteract the continuous evolution of materials embedded into cars. Finally, Farel et al. (2013b) proposed a model investigating the potential cost and benefit of ELV glazing recycling for all of the value-chain stakeholders, and for the network as a whole.
Given the interesting results and the strong research affinity with (Zamudio-Ramirez, 1996) work, the same SD model was taken into account as reference by this paper. The original SD model was updated and upgraded, before applying it to the Italian context. The updating process interested constant input values of the original SD model, substituted with Italian data coming from both field interviews and the scientific literature. Instead, the upgrading process interested the materials mix taken into account by the original SD model, by considering also the ones coming from the recovery of automotive electronic components (e.g. hazardous, rare and precious metals, rare earths and epoxy resins). Automotive electronics recovery was embedded in the original SD model because the international literature ((Restrepo et al., 2017); (Cucchiella et al., 2016a); (Widmer et al., 2015); (Wang and Chen, 2011)) agrees about its potential of improving current economic performances of

the actors involved in any ELV recovery chain, by making it more profitable and sustainable than current practices where automotive electronic components end either into landfills or incinerators. Current economic performances of the Italian ELV recovery chain have been assessed and compared to the ones potentially reachable through the management of automotive electronics. This way, companies could adopt this simulation tool to assess future scenarios and optimize their decisional processes.

3. Research methodology

The SD methodology is adopted in this study for evaluating the economic performance of the Italian ELV recovery chain. Vensim® Professional was the software adopted within this work for the development of the whole SD model, its simulation, validation and optimization. This way, the economic performance of the Italian ELV recovery chain can be fully assessed with a unique decision-support tool. Vensim® Professional was selected as the best solution for doing that because it is the most commonly used software dedicated to SD models design and simulation (e.g. (Sterman, 2000)). Many SD models present in literature – and related to very different contexts (e.g. (Asif et al., 2015); (Dong et al., 2012); (Yuan et al., 2011)) – were developed with this software. In the following sub-sections, a description of the main assumptions, the conceptual framework, the overall structure, the mathematical model and the main economic and technical input sustaining the model are presented.

3.1. SD model assumptions

The model taken into account within this paper assumes that the Italian ELV recovery chain is represented by only one automaker, one dismantler and one shredder. This assumption is the same taken into account by Zamudio-Ramirez (1996). Another hypothesis is related to the vehicle's materials composition. ELVs are considered to be made only of ferrous metals (steel), nonferrous metals (aluminium, magnesium and copper) and plastics. Other materials are not taken into account because of their low amounts in comparison to the overall mass of a generic car. Automakers are assumed to be able to decide about the materials composition of platforms under development. This way, cars already in the market are not influenced by these changes. Dismantlers are hypothesised to make revenues from two sides, or the selling of spare parts on the secondary market and car hulks to shredders. However, within this paper dismantler's economic performances are considered only in terms of car hulks selling. Finally, shredders are assumed to make money only through the direct selling of ferrous and nonferrous scrap metals to the secondary raw materials market. External variables are represented by both the Gross Domestic Product (GDP) of the reference nation and materials market prices. GDP is considered to be strongly correlated to car sales and, hence, to the demand of steel. This way, it is indirectly correlated also to the value of car hulks (and related subsystems). Materials market prices heavily influence the expected revenues of shredders. In addition, some cost items are also considered to be exogenous, like the labour and landfilling costs. The whole number of cars on the road is subdivided into seven groups (or cohorts), basing on their age. The considered timeframe goes from 2015 back to 1994. Cars with an age with-in 0 and 9 years are considered as "new cars". Instead, cars from 10 to 21 years are considered as "old cars". New cars (representing approximately 20% of the total) are the preferred source of spare parts for the secondary market. These parts are generally sold at 50% of the new part price. Old cars are processed only for the material value they embed.

3.2. Conceptual framework

The conceptual framework of the SD model is represented in **Figure 2**.

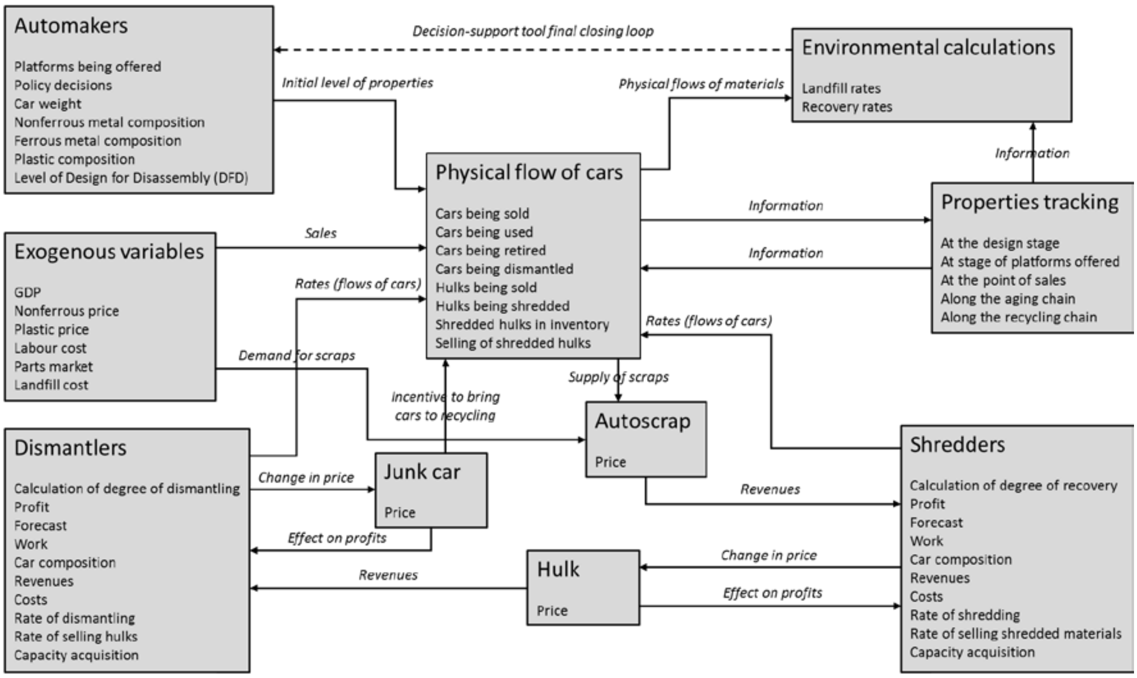

Figure 2. Conceptual framework of the decision-support tool (Adapted from (Zamudio-Ramirez, 1996))

The conceptual framework can be seen as a group of ten elements, three of which relate on the prices of junk cars, car hulks and metal scraps.

The first element (titled “Automakers”) represents the automaker’s point of view. From its perspective, automakers can influence the ELV recovery chain through several decisions on type, number and composition of new cars launched into the market. Basing on the materials content and the application of Design for Disassembly (DFD) techniques, ELVs entering the recovery chain can favour (or obstacle) the overall performance of both dismantlers and shredders.

The second element (titled “Exogenous variables”) is represented by exogenous variables. These are all the variables that cannot be controlled by any of the actors considered within the context. They can be distinguished among: (i) nation-dependent variables (e.g. GDP), (ii) market-dependent variables (e.g. materials and spare parts prices) and cost items (e.g. labour cost and landfilling fees).

The third element (titled “Physical flow of cars”) represents the physical flow of cars. The intent is to map the entire process followed by a car during the recovery chain, trying to continuously check the mass balance between input and output materials.

The fourth element (titled “Environmental calculations”) represents the environmental impact of the whole ELV recovery chain. In this case, landfill and recovery rates are the only two dimensions taken into account.

The fifth element (titled “Properties tracking”) represent the set of properties related to each car. Its aim is the same as the third element, or guaranteeing the correct balance during the entire process, but at material level.

The sixth and seventh elements (titled “Dismantlers” and “Shredders”) represent the dismantler’s and shredder’s point of view. These are described together because of their similar logic. For both of these actors the model assesses a set of different variables. They can macroscopically be divided between economic and operational ones. Among the economic items there are all the variables related to revenues and costs representative of the activity done by the actors. Instead, operational variables consider elements related to the plant (e.g. capacity, recovery rates and forecasts).
Finally, the eighth, ninth and tenth elements (titled “Junk car”, “Hulk” and “Autoscrap”) represent the mechanisms through which market prices of specific automotive wastes (e.g. junk cars, car hulks and metal scraps, respectively) are defined within the ELV recovery chain.

3.3. SD model structure

A representative picture of the SD model structure is reported in **Figure 3** under the form of a simplified causal-loop diagram. Arrows represent a causal relationship between two variables. Positive or negative signs represent the type of relation. This way, a positive (negative) change in the source variable causes a positive (negative) change also in the target variable. The following causal-loop diagram reports the main balancing feedbacks governing the long-run ELV recovery chain.
Given the strong relation between the gross domestic product and the purchasing power of people, the whole structure starts from the GDP value. It influences positively both the production and the sales of new cars. The higher the number of new cars sold, the higher the number of old cars retired from the market. These last ones represent the input material for the ELV recovery chain. An increase in the retirement of cars becomes an increase of dismantled and shredded cars. Then, the recovered material goes to influence both the scrap and raw material prices and, so, the demand of raw materials from the market. The price of scraps influences shredders profit and, so, their investments in additional capacity. Indirectly, the price of scraps influences also the price of hulks, or the trading element between shredders and dismantlers. Subsequently, the price of hulks influences the dismantler’s profit. This way, also the junk car price is influenced and, so, the willingness of private owners to bring their cars to recycling. This last effect can be easily described. The higher the amount of junk cars stored in the backyards of dismantlers, the lower the value they want to pay for other cars. Hence, people are not pushed to buy new cars.
Trying to describe the whole structure, we can assess the effect of a change in GDP on different variables. An increase in GDP can cause a positive change in the amount of dismantled and shredded cars and, so, on the amount of scraps. The augment in scraps lowers their price and the one for virgin materials, by favouring its market demand. However, a reduction of scrap prices negatively influences the shredder’s profit and the price of hulks they want to pay for additional material to treat. This way, dismantlers accumulate hulks in their backyards and the value of junk cars goes down, together with the willingness to pay for additional cars. In contrast, a reduction in GDP decreases the demand for virgin and secondary materials, but enables an increase in scrap prices that favours both shredders and dismantlers. From one side, higher scrap prices support shredders profits. This way, they are willing to pay a higher price to gather additional materials to treat. At the same time, dismantlers can sell their hulks with a higher price, their stocks go down and the value of additional junk cars increases, by enabling the willingness to bring cars to recycle in people.

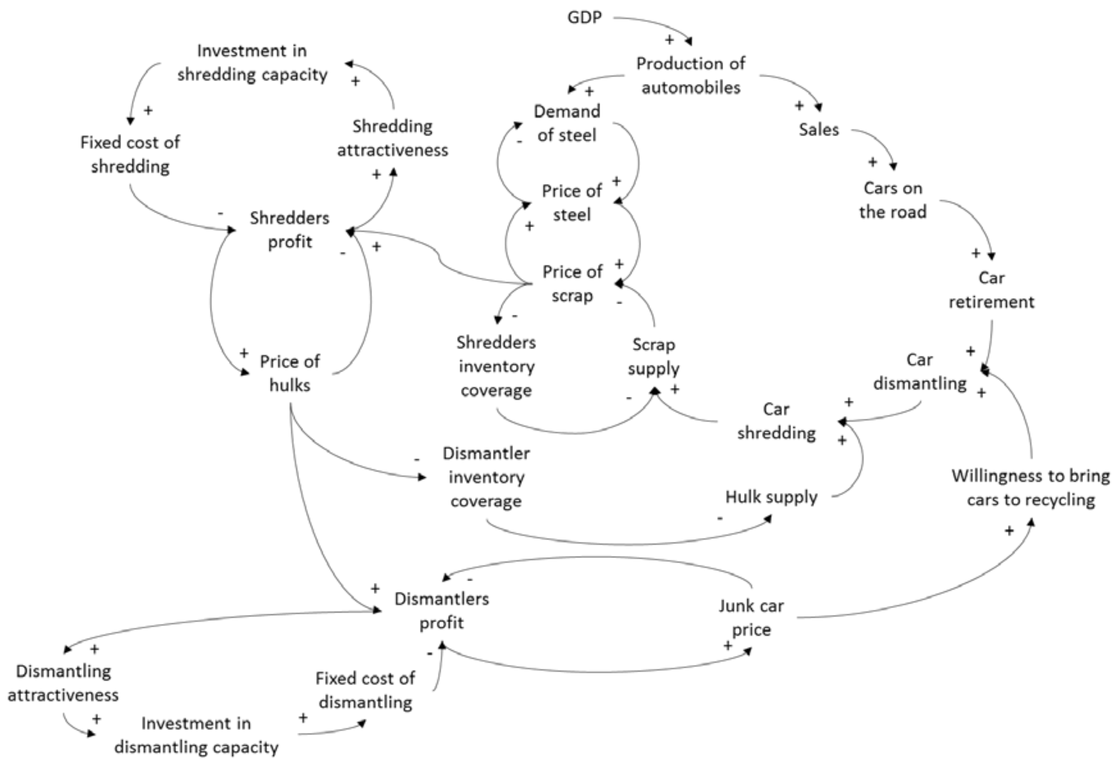

Figure 3. Structure of the SD model (Adapted from (Zamudio-Ramirez, 1996))

3.4. ELV recovery chain economic model

The profitability of both a generic dismantler and shredder can be assessed only if their costs and revenues structures are known. For this reason, a dedicated MS Excel economic quantification tool was developed, following what was been already done in the reference work. A simplified version of the economic model developed by the authors can be described below, by distinguishing between dismantlers and shredders equations. From the dismantler's point of view, the economic model can be simplified as follows (see **Table 4** for details):

$$\Pi_{tot} = R_{tot} - C_{tot} \quad (1)$$
$$R_{tot} = R_{recycled\ mat.} + R_{selling\ hulks} + R_{PCB\ recovery} \quad (2)$$
$$R_{recycled\ mat} = p_{recycled\ mat} * Q_{recycled\ mat} \quad (3)$$
$$R_{selling\ hulks} = p_{hulks} * Q_{hulks} \quad (4)$$
$$R_{PCB\ recovery} = p_{PCB} * Q_{PCB} \quad (5)$$
$$C_{tot} = C_{variable} + C_{fixed} \quad (6)$$
$$C_{variable} = C_{junk\ car} + C_{labour} + C_{energy} + C_{PCB\ recovery} \quad (7)$$
$$C_{junk\ car} = p_{junk\ car} * Q_{junk\ car} \quad (8)$$
$$C_{labour} = c_{labour} * Q_{hour/car} \quad (9)$$
$$C_{energy} = c_{energy} * Q_{energy/car} \quad (10)$$
$$C_{PCB\ recovery} = c_{PCB\ recovery} * Q_{PCB} \quad (11)$$
$$C_{fixed} = C_{substitution\ (XX\%)} \quad (12)$$

From the shredder’s point of view, the economic model can be simplified as follows:

$\Pi_{tot} = R_{tot} - C_{tot}$ (13)

$R_{tot} = R_{ferrous\ scrap} + R_{nonferrous\ scrap} + R_{PCB\ recovery}$ (14)

$R_{ferrous\ scrap} = p_{ferrous\ scrap} * Q_{ferrous\ scrap}$ (15)

$R_{nonferrous\ scrap} = p_{nonferrous\ scrap} * Q_{nonferrous\ scrap}$ (16)

$R_{PCB\ recovery} = p_{PCB} * Q_{PCB}$ (17)

$C_{tot} = C_{variable} + C_{fixed}$ (18)

$C_{variable} = C_{hulks} + C_{transport} + C_{energy} + C_{var\ maintenance} + C_{landfilling} + C_{PCB\ recovery}$ (19)

$C_{hulks} = p_{hulks} * Q_{hulks}$ (20)

$C_{transport} = p_{transport} * Q_{transport}$ (21)

$C_{energy} = c_{energy} * Q_{energy}$ (22)

$C_{var\ maintenance} = c_{var\ maintenance} * Q_{hulks}$ (23)

$C_{landfilling} = c_{landfilling} * Q_{hulks}$ (24)

$C_{PCB\ recovery} = c_{PCB\ recovery} * Q_{PCB}$ (25)

$C_{fixed} = C_{operator} + C_{administrative} + C_{fix\ maintenance} + C_{insurance} + C_{capacity}$ (26)

$C_{operator} = c_{operator} * Q_{hulks}$ (27)

$C_{administrative} = c_{administrative} * Q_{hulks}$ (28)

$C_{fix\ maintenance} = c_{fix\ maintenance} * Q_{hulks}$ (29)

$C_{insurance} = c_{insurance} * Q_{hulks}$ (30)

$C_{capacity} = c_{capacity} * Q_{hulks}$ (31)

Table 4. Nomenclature of the ELV recovery chain economic model

Nomenclature			
Π_{tot}	Total profit	$C_{substitution\ (XX\%)}$	Plant substitution cost
R_{tot}	Total revenue	$R_{ferrous\ scrap}$	Revenue from ferrous scraps
C_{tot}	Total cost	$R_{nonferrous\ scrap}$	Revenue from nonferrous scraps
$R_{recycled\ mat}$	Revenue from recycling	$p_{ferrous\ scrap}$	Market price of ferrous scraps
$R_{selling\ hulks}$	Revenue from selling hulks	$Q_{ferrous\ scrap}$	Quantity of ferrous scraps per year
$R_{PCB\ recovery}$	Revenue from PCB recovery	$p_{nonferrous\ scrap}$	Market price of nonferrous scraps
$p_{recycled\ mat}$	Market price of recycled materials	$Q_{nonferrous\ scrap}$	Quantity of nonferrous scraps per year
$Q_{recycled\ mat}$	Quantity of recycled materials	C_{hulks}	Hulks cost
p_{hulks}	Market price of hulks	$C_{transport}$	Transportation cost
Q_{hulks}	Quantity of hulks per year	$C_{var\ maintenance}$	Variable maintenance cost
p_{PCB}	Market price of PCBs	$C_{landfilling}$	Landfilling cost
Q_{PCB}	Quantity of PCBs per year	$c_{transport}$	Unit transportation cost (€/ton)
$C_{variable}$	Variable costs	$Q_{transport}$	Quantity of tons transported per year
C_{fixed}	Fixed costs	$c_{var\ maintenance}$	Unit variable maintenance cost (€/ton)
$C_{junk\ car}$	Junk cars cost	Q_{hulks}	Quantity of hulks per year
C_{labour}	Labour cost	$c_{landfilling}$	Unit landfilling cost (€/ton)
C_{energy}	Energy cost	$C_{operator}$	Operator cost
$C_{PCB\ recovery}$	PCB recovery cost	$C_{administrative}$	Administrative cost
$p_{junk\ car}$	Market price of junk cars	$C_{fix\ maintenance}$	Fixed maintenance cost
$Q_{junk\ car}$	Quantity of junk cars per year	$C_{insurance}$	Insurance cost

c_{labour}	Unit labour cost (€/hour)	$C_{capacity}$	Capacity cost
$Q_{hour/car}$	Hours per car	$c_{administrative}$	Unit administrative cost (€/hour)
c_{energy}	Unit energy cost (€/KWh)	$c_{fix\ maintenance}$	Unit fixed maintenance cost (€/ton)
$Q_{energy/car}$	KWh per car	$c_{insurance}$	Unit insurance cost (€/ton)
$c_{PCB\ recovery}$	Unit PCB recovery cost (€/PCB)	$c_{capacity}$	Unit capacity cost (€/ton)

3.5. Economic and technical input

All the economic data embedded in the MS Excel tool were gathered directly from interviews and the scientific literature. The lacking ones were both autonomously quantified (following the logics of the reference wok) or maintained the same, like in the original SD model (see **Table 5** and **Table 6** for details).

Table 5. Average Italian dismantler economic and technical input (Sources: ACI, ADA, ANFIA, Confindustria, (Santochi et al., 2002), direct interviews)

Sectorial data					
Variable	Value	Unit of measure	Variable	Value	Unit of measure
Total deregistered	200,000	cars/month	Disassembly time	1,22	hour/car
Monthly total capacity	112,000	cars/month	Depollution time	0.78	hour/car
Utilization rate	70%		Total dismantling time	2.00	hour/car
Installed capacity/plant	960	cars/year	Avg. plant lifetime	15	years
Variable costs					
Variable	Value	Unit of measure	Variable	Value	Unit of measure
Junk car price	20.00	€/car	Energy cost	0.63	€/car
Labour cost	40.00	€/car	PCB recovery cost	18.42	€/car
Revenue sources					
Variable	Value	Unit of measure	Variable	Value	Unit of measure
Unit recycling revenues	20.83	€/car	Selling hulks revenues	124.95	€/car
Avg. hulks weight	892.5	kg/car	PCB recovery revenues	46.88	€/car
Avg. hulk price	140.00	€/car			
Fixed costs					
Variable	Value	Unit of measure	Variable	Value	Unit of measure
Substitution cost (100%)	34.72	€/car	Substitution cost (70%)	49.60	€/car
Total costs			128.65 €/car		
Total revenues			192.67 €/car		
Total profits			64.01 €/car		

Table 6. Average Italian shredder economic and technical input (Sources: ACI, AIRA, ANFIA, Confindustria, (Berzi et al., 2013), direct interviews)

Sectorial data					
Variable	Value	Unit of measure	Variable	Value	Unit of measure
Total cars shredded	200,000	cars/month	Installed capacity/plant	7500	tons/month
Total tons shredded	178,500	tons/month	Shredder utilization rate	40%	
Materials distribution data					
Variable	Value	Unit of measure	Variable	Value	Unit of measure
Ferrous metals	70.00%		Avg. car weight	1050	kg/car

Non-ferrous metals	5.00%		Avg. hulks weight	892.5	kg/car
ASR fraction	25.00%		Total cars shredded	3361	cars/month
Variable costs					
Variable	Value	Unit of measure	Variable	Value	Unit of measure
Avg. hulk price	124.95	€/car	Variable maintenance cost	3.51	€/car
Transportation cost	13.39	€/car	ASR landfilling cost	15.17	€/car
Energy cost	1.76	€/car	PCB recovery cost	18.42	€/ton
Revenue sources					
Variable	Value	Unit of measure	Variable	Value	Unit of measure
Scrap ferrous price	240.00	€/ton	Nonferrous revenues	48.11	€/car
Scrap nonferrous price	1100.00	€/ton	PCB recovery revenues	46.88	€/car
Scrap metal revenues	148.44	€/car			
Fixed costs					
Variable	Value	Unit of measure	Variable	Value	Unit of measure
Labour cost	7.24	€/car	Insurance cost	4.10	€/car
Administrative cost	4.00	€/car	Capacity cost	2.98	€/car
Fixed maintenance cost	3.15	€/car			
Total costs			198.66 €/car		
Total revenues			243.43 €/car		
Total profits			44.77 €/car		

4. Case study and input data: The Italian ELV recovery chain

Once finalized the SD model, the attention was given to a real industrial context, like the Italian one. The next sub-sections describe, in numerical terms, the current situation of the Italian context.

4.1. The European and Italian ELVs management context

The most updated estimates say that the only Europe generates yearly from 7 to 14 million tons of ELVs, with an annual growth rate from 2% to 8%. A general perspective of EU ELVs volumes can be seen in the following **Table 7**.

Table 7. European ELV volumes (Source: Eurostat)

	2007	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**
EU-28 (1)	**:**	**:**	**:**	**:**	**:**	**6,290,000**	**6,250,000**
EU-27 (1)	**6,500,000**	**6,270,000**	**9,000,000**	**7,350,000**	**6,750,000**	**6,250,000**	**6,220,000**
Belgium	127,949	141,521	140,993	170,562	165,016	160,615	134,506
Bulgaria	23,433	38,600	55,330	69,287	62,937	57,532	61,673
Czech Republic	72,941	147,259	155,425	145,447	132,452	125,587	121,838
Denmark	99,391	101,042	96,830	100,480	93,487	106,504	125,650
Germany	456,436	417,534	1,778,593	500,193	466,160	476,601	500,322
Estonia	12,664	13,843	7,528	7,268	11,413	12,835	14,712
Ireland	112,243	127,612	152,455	158,237	134,960	102,073	92,467
Greece	47,414	55,201	115,670	95,162	112,454	84,456	86,205
Spain	881,164	748,071	952,367	839,637	671,927	687,824	734,776
France	946,497	1,109,876	1,570,593	1,583,283	1,515,432	1,209,477	1,115,280
Croatia	:	:	:	:	:	35,213	32,135
Italy	**1,692,136**	**1,203,184**	**1,610,137**	**1,246,546**	**952,461**	**902,611**	**876,052**

Cyprus	2,136	14,273	17,303	13,219	17,145	17,547	13,212
Latvia	11,882	10,968	10,590	10,640	9,387	10,228	9,003
Lithuania	15,906	19,534	19,656	23,351	26,619	22,885	26,482
Luxembourg	3,536	2,865	6,908	6,303	2,341	2,834	2,290
Hungary	43,433	37,196	26,020	15,907	13,043	15,357	14,897
Malta	:	:	:	330	2,526	2,530	1,198
Netherlands	166,004	152,175	191,980	232,448	195,052	187,143	183,451
Austria	62,042	63,975	87,364	82,144	80,004	64,809	73,993
Poland	171,258	189,871	210,218	259,576	295,152	344,809	402,416
Portugal	90,509	107,746	107,946	107,419	77,929	92,008	92,112
Romania	36,363	51,577	55,875	190,790	128,839	57,950	:
Slovenia	8,409	6,780	7,043	6,807	6,598	5,447	:
Slovakia	28,487	39,769	67,795	35,174	39,717	33,469	36,858
Finland	15,792	103,000	96,270	119,000	136,000	119,000	99,300
Sweden	228,646	150,197	133,589	170,658	184,105	185,616	189,748
United Kingdom	1,138,496	1,210,294	1,327,517	1,157,438	1,220,873	1,163,123	1,149,459
Iceland	:	9,386	5,109	4,195	4,075	5,824	4,463
Liechtenstein	82	91	72	107	94	114	326
Norway	95,128	130,018	95,000	112,537	124,563	119,905	141,452

(1) Eurostat estimates for 2007–09 and 2013. For reasons of comparison, EU-27 data are also shown for 2012 and 2013, although EU-28 data are available.

Considering the previous 2013 data reported in **Table 7**, United Kingdom is the first source of ELVs in Europe, followed by France, Italy, Spain and Germany. Italy alone generated in 2013 an annual amount of about 876k tons of ELVs.

In a broad perspective, data about Italian ELVs management practices can be gathered from several information sources. They can be distinguished in: (i) official database (e.g. Eurostat), (ii) official institutions (e.g. the Italian Ministry of Infrastructures and Transports (MIT), the Italian Automobile Club (ACI), the Italian Automotive Public Register (UMC), the Italian Institute for the Environmental Protection and Research (ISPRA)), (iii) industrial entities (e.g. the Italian Confederation of Industries (CONFINDUSTRIA)) and (iv) national sectorial associations (e.g. the Italian Association of the Automotive supply chain (ANFIA), the Italian Associations of Automotive Dismantlers (CAR and ADA), the Italian Association of Automotive Recyclers (AIRA)). All of these sources were assessed by the authors. Some of them were reached only through their official website, others were directly interviewed (see **Table 8 - Table 12** for details).

Table 8. Some Italian cars 2015 data (Source: ACI, ANFIA)

Cars age	Circulating 2015	Deregistered 2015	Demolished 2015
0-3 years	4.374.400	31.051	20.751
3-6 years	5.018.196	54.363	36.331
6-9 years	6.506.229	86.007	57.478
9-12 years	6.092.160	176.949	118.254
12-15 years	5.100.336	312.093	208.571
15-18 years	3.583.165	327.445	218.830
18+ years	6.676.747	361.729	241.742
Total 2015	37.351.233	1.349.637	901.957

Table 8 reports some interesting data about the Italian automotive market. Since this table it is possible to comprehend that there is a wide distinction between deregistered and demolished cars. Italy, like most of the other EU countries having the widest number of circulating cars (e.g. Germany, France and Spain) suffer of a typical issue of illegal exports of ELVs. Those ELVs that should be recycled in Italy, instead, are sold by official Italian dealers to foreign traders as “second-hand cars”. However, those “cars” will not be re-registered in the final market of the trader, but recycled there. This way, an illegal transfer of automotive wastes (only in Italy represents 30% of generated ELVs yearly) continues to expand, especially in eastern EU countries. Given this effect, ELV recovery chains in western EU countries are obliged to either buy volumes abroad or reduce their capacity to survive.

Table 9. Some Italian cars 2015 monthly data (Source: ACI, ANFIA)

Cars age	Deregistered/month 2015	Demolished/month 2015	Monthly/Total deregistered (%)	Cumulated amount
0-3 years	2.588	1.729	0,02301	0,02301
3-6 years	4.530	3.028	0,04028	0,06329
6-9 years	7.167	4.790	0,06373	0,12701
9-12 years	14.746	9.855	0,13111	0,25812
12-15 years	26.008	17.381	0,23124	0,48936
15-18 years	27.287	18.236	0,24262	0,73198
18+ years	30.144	20.145	0,26802	1,00000

Table 9 shows the distribution of 2015 ELV monthly volumes basing on the car ages. This amount was, then, used to define the monthly/total deregistered ratio and, consequently, the cumulated amount of ELVs by age. Those data will be exploited by the next calculation steps to define the historical and equilibrium amounts and percentages of ELVs to be embedded into the SD model.

Table 10. Italian 2015 new registered cars (Source: Eurostat, MIT, ACI)

Year	New registrations	Year	New registrations	Year	New registrations	Year	New registrations
1996	1.843.366	**2001**	2.379.980	**2006**	2.543.157	**2011**	1.764.592
1997	2.389.892	**2002**	2.235.948	**2007**	2.514.905	**2012**	1.403.043
1998	2.437.718	**2003**	2.516.972	**2008**	2.193.822	**2013**	1.311.334
1999	2.312.309	**2004**	2.743.769	**2009**	2.176.940	**2014**	1.376.185
2000	2.359.674	**2005**	2.441.978	**2010**	1.971.830	**2015**	1.593.857
Annual average sales 1996-2015				2.125.564			
Monthly average sales 1996-2015				177.130			
Annual average sales 1996-2007 (pre-crisis)				2.393.306			
Monthly average sales 1996-2007 (pre-crisis)				199.442			

Considering **Table 10** data, it is possible to compare the automotive sector health in pre- and post-economic crisis time periods. Annual and Monthly sales were higher in the 1996-2007 period than in 2015 (-1.1 million cars sold than in 2004). To this aim, the 1996-2007 average data (e.g. 2.4 million cars sold/year and 200k cars sold/month) were considered as more representative of the real Italian market potential and adopted within the SD model like the equilibrium level. Instead, the annual and monthly 2015 data (e.g. 1.6 million cars sold/year and 133k cars sold/month) were considered in the SD model as the historical level.

Table 11. Calculation of Italian 2015 new and old deregistered cars (Source: MIT, ACI, ANFIA)

Groups	Circulating cars				Monthly deregistered cars					
	Hist.	**%**	**Equil.**	**%**	**Hist.**	**%**	**Equil.**	**%**	**Hist. new**	**Equil. new**
0-3 years	4.374.400	11,7%	7.200.000	21,4%	2.588	2,3%	4.601	2,3%	14.285	40.215
3-6 years	5.018.196	13,4%	7.034.352	20,9%	4.530	4,0%	12.366	6,2%		
6-9 years	6.506.229	17,4%	6.589.170	19,6%	7.167	6,4%	23.247	11,6%	12,70%	20,11%
9-12 years	6.092.160	16,3%	5.752.262	17,1%	14.746	13,1%	41.244	20,6%	**Hist. old**	**Equil. old**
12-15 years	5.100.336	13,7%	4.267.483	12,7%	26.008	23,1%	58.010	29,0%	98.185	159.785
15-18 years	3.583.165	9,6%	2.179.132	6,5%	27.287	24,3%	44.308	22,2%		
18+ years	6.676.747	17,9%	584.050	1,7%	30.144	26,8%	16.224	8,1%	87,30%	79,89%
Total 2015	37.351.233		33.606.448		112.470		200.000			

Table 11 reports the overall data used to define the Italian new and old deregistered cars at historical and equilibrium levels. Starting from historical 2015 data about aging groups of circulating cars and a hypothesised equilibrium amount (average value) of new registered cars in a period of three years, it was possible to define the overall amount of monthly historical and equilibrium deregistered cars, dividing them between new (age from 0 to 9 years) and old (age from 9 to 18+) ones. Like described above, this calculation was possible only by considering monthly deregistered cars percentages and cumulated amounts. These last amounts (both percentages and amounts) represent input data of the SD model.

4.2. Italian ELVs management inputs

The current Italian ELV recovery chain is constituted by several actors that, acting independently, are able to recover materials and parts from cars. Generally, an ELV recovery chain can be described as a group of three actors, like automakers, dismantlers and shredders. In addition, a series of auxiliary actors can be present, like foundries, raw material brokers, secondary spare parts and metal scrap traders.

Table 12. Italian official ELVs dismantlers and shredders (Source: Confindustria)

	2003	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
Dismantlers	1562	1418	1489	1388	1407	1313	:	:	:	1348	1500	1510
Shredders	:	:	27	:	:	36	:	:	33	36	33	35

Considering data reported in **Table 12**, there is a relevant presence of dismantlers (estimated in about 1510 companies in 2014) – uniformly distributed in the country – and about 35 shredders mainly distributed in the northern part of Italy. From the automaker's perspective, only one Italian company is taken into account within this study. During this work, many of these actors were directly interviewed, asking for quantitative data to be embedded within the SD model under development. However, average data will be presented and discussed within the paper, for confidential reasons. Considering an initial list of 51 companies (among sectorial associations, automakers, dis-

mantlers, shredders and spare parts traders), 30 of them accepted to be interviewed, by sharing valuable information about their business. The interview was always implemented through a set of open questions regarding all of the constant inputs of the SD model.
Trying to define some realistic hypotheses about Italian dismantlers' and shredders' plants installed capacity, some initial distinctions were done. First of all, the overall installed capacity is currently unsaturated, given illegal flows previously described. This way, annual demolished amounts represent only a 70% of the potential capacity available. Secondly, not all ELVs are cars, but also trucks, buses, motorcycles and any other kind of vehicle considered by the ELV Directive. This way, cars represent the 90% of yearly generated ELVs. By taking into account all of these information, a set of important data to be embedded within the SD model were found. From the dismantlers' point of view, the authors considered an average of 1400 plants, with an overall installed capacity of about 1.3 million cars/year (about 112k cars/month) and a utilization rate of 70%. This way, a generic Italian dismantling centre's capacity can be quantified in about 960 cars/year (80 cars/month). From the shredders' point of view, the authors considered an average of 35 plants, with an overall installed capacity of about 3.1 million tons/year (about 262k tons/month) and a utilization rate of 70%. %. This way, a generic Italian shredding centre's capacity can be quantified in about 90,000 tons/year (7500 tons/month).

5. Results and discussion

Once finalized the SD model and quantified – in numerical terms – the Italian context, the final step was the validation process. The following sub-sections describe into detail the main findings coming from the application of the SD model in the Italian context, discussing them from different perspectives.

5.1. SD model validation

Once identified all the equations reported in Section 3.4 and all the input data reported in Section 3.5, the SD model was tested intensively, by varying values of constant inputs at the base of the model and assessing different scenarios. Results were, then, discussed with a selected group of experts for a final refinement of specific parameters. **Figure 4** and **Figure 5** illustrate the response of the model on the introduction of the automotive electronics recovery process within the current ELV recovery chain. The first picture considers that the automotive electronics recovery process will be managed by shredders. Contrarily, the second picture considers that dismantlers will manage those process. Taking into account the graphs reported in **Figure 4**, there is a clear distinction in terms of effects between dismantlers and shredders. In this scenario, dismantlers will be only partially responsible for the recovery of automotive electronics. Their involvement will consider the only disassembly of automotive electronic components from ELVs and their direct selling to shredders. Instead, shredders will be responsible for the final recovery of materials from scrap automotive components. This means that a dedicated recovery plant will be owned by shredders, in addition to current shredding and separation equipments. **Figure 4a** and **Figure 4b** show the impact of the adoption of automotive electronics recovery processes on the economic performance of dismantlers. Here, like in all of the following pictures, economic performances of both dismantlers and shredders are mapped into two ways, or cumulative and semester profits. In this first scenario, even if dismantlers will participate only partially to the recovery process, it is evident that the recovery of electronic components could offer a relevant improvement also for them, even immediately. The cumulative profit of dismantlers could strongly increase. Considering the hypothesized trend, within 50 years the overall business of dismantlers could go from 5.8 billion Euros to 7.5 billion Euros. The same behaviour can be found also in terms of semester profits of the overall sector, stabilizing within 50 years to about 80 million Euros (instead of about 37.5 million Euros without electronics). Obviously, the best improvement in terms of economic performances can be expected for shredders. Even if the recovery of automotive electronics will require a considerable investment in additional plants, these expenses will be completely recovered in few years. Cumulative profits related to the overall business of shredders could strongly increase, reaching within 50 years a potential level of about 12.4 billion Euros (instead of about 4.8 billion Euros without electronics). The same effect can be described in terms of semester profits, stabilizing in 142.5 million Euros within 50 years instead of 56.3 million Euros without electronics.

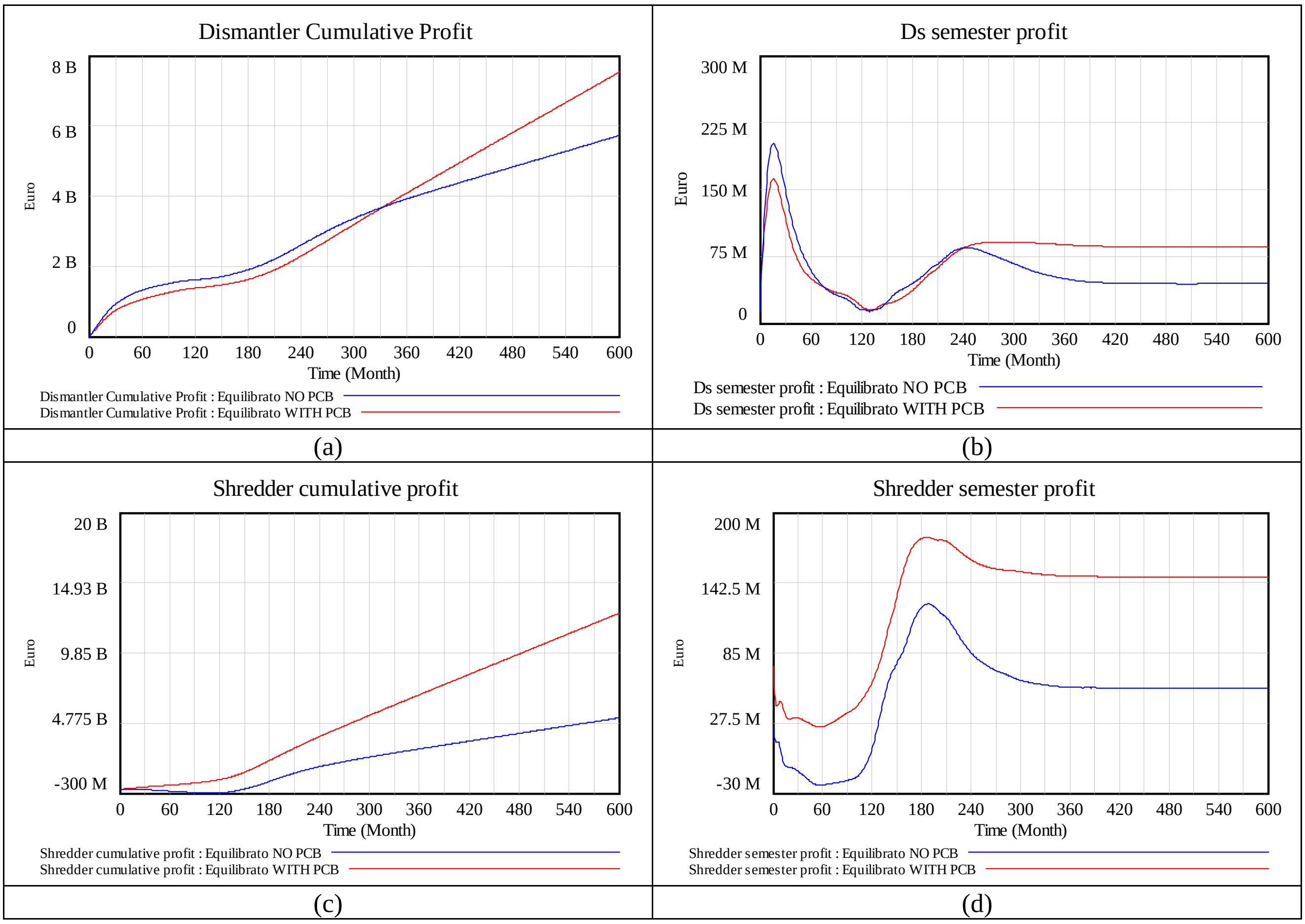

Figure 4. Effects of automotive PCB recovery on Sh and Ds profits – Shredders lead

A similar result can be obtained by taking into account the graphs reported in **Figure 5**. Also in this case, there is a clear distinction in terms of effects between dismantlers and shredders. However, in this scenario shredders will not be involved in the recovery of automotive electronics, a process completely managed by dismantlers. Dismantlers, in addition to usual disassembly and collection activities, will be responsible for the final recovery of materials from scrap automotive components. This means that a dedicated recovery plant will be owned by dismantlers. **Figure 5a** and **Figure 5b** show the impact of the adoption of automotive electronics recovery processes on the economic performance of dismantlers. Also here, economic performances of both dismantlers and shredders are mapped into two ways, or cumulative and semester profits. In this second scenario, it is evident that the recovery of electronic components could offer a relevant improvement for dismantlers, even immediately. The cumulative profit of dismantlers could strongly increase. Considering the hypothesized trend, within 50 years the overall business of dismantlers could go from 5.8 billion Euros to 15 billion Euros. The same behaviour can be found also in terms of semester profits of the overall sector, stabilizing within 50 years to about 150 million Euros (instead of about 37.5 million Euros without electronics). Obviously, the best improvement in terms of economic performances can be expected for shredders. In this case, shredders would continue in doing their business as usual. Without any impact coming from this new kind of activity done by dismantlers.

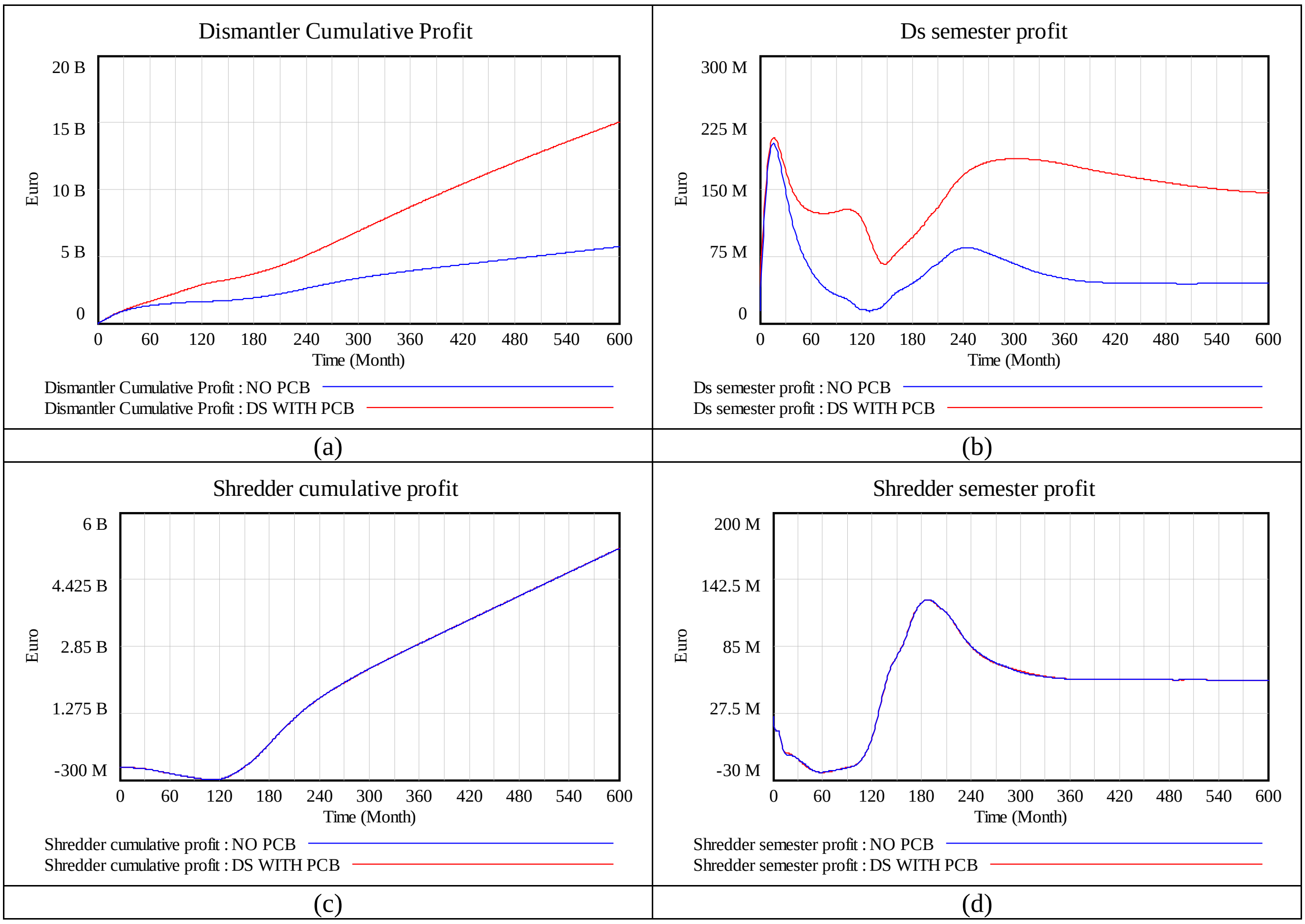

Figure 5. Effects of automotive PCB recovery on Sh and Ds profits – Dismantlers lead

5.2. Analysis of factors influencing the economic performance

A direct involvement of managers from several companies involved in the Italian ELV recovery chain allowed defining what are the main variables embedded in the current SD model influencing their economic performances once automotive electronics will start to be recovered correctly. Those variables were identified in:

- Constant properties (e.g. nonferrous metals composition) of ELVs entering the recovery process

- Price of nonferrous metals leaving the recovery process. A detail on the impact of a change in those two variables is described in the next sub sections.

5.2.1. Constant properties (nonferrous metals composition) of ELVs

One of the first variables identified by industrial actors as potentially influenced by the increasing presence of electronics in cars is the overall materials composition of vehicles. Even if limited (estimates speak of about 1% on the total average mass of a car), the presence of electronics in cars could reduce the overall amount of iron. Given that iron is, currently, the main source of revenue for both dismantlers and shredders, its reduction could mean a direct reduction of their revenues. However, a good answer to this issue can be found in the following **Figure 6**. Also in this case, cumulative and semester profits of both dismantlers and shredders have been compared. The main hypothesis done during this simulation was that the percentage in nonferrous metals could rise from current 9% to about 10%). From a dismantler's view, the reduction in iron could negatively affects their business, especially in the first assessed period. However, wit time this change in materials composition of cars could offer a better economic perspective than now (this is visible especially in terms of semester profits). From a shredder's perspective, the effect is less evident. Both in terms of cumulative and semester profits their economic performances will be very similar.

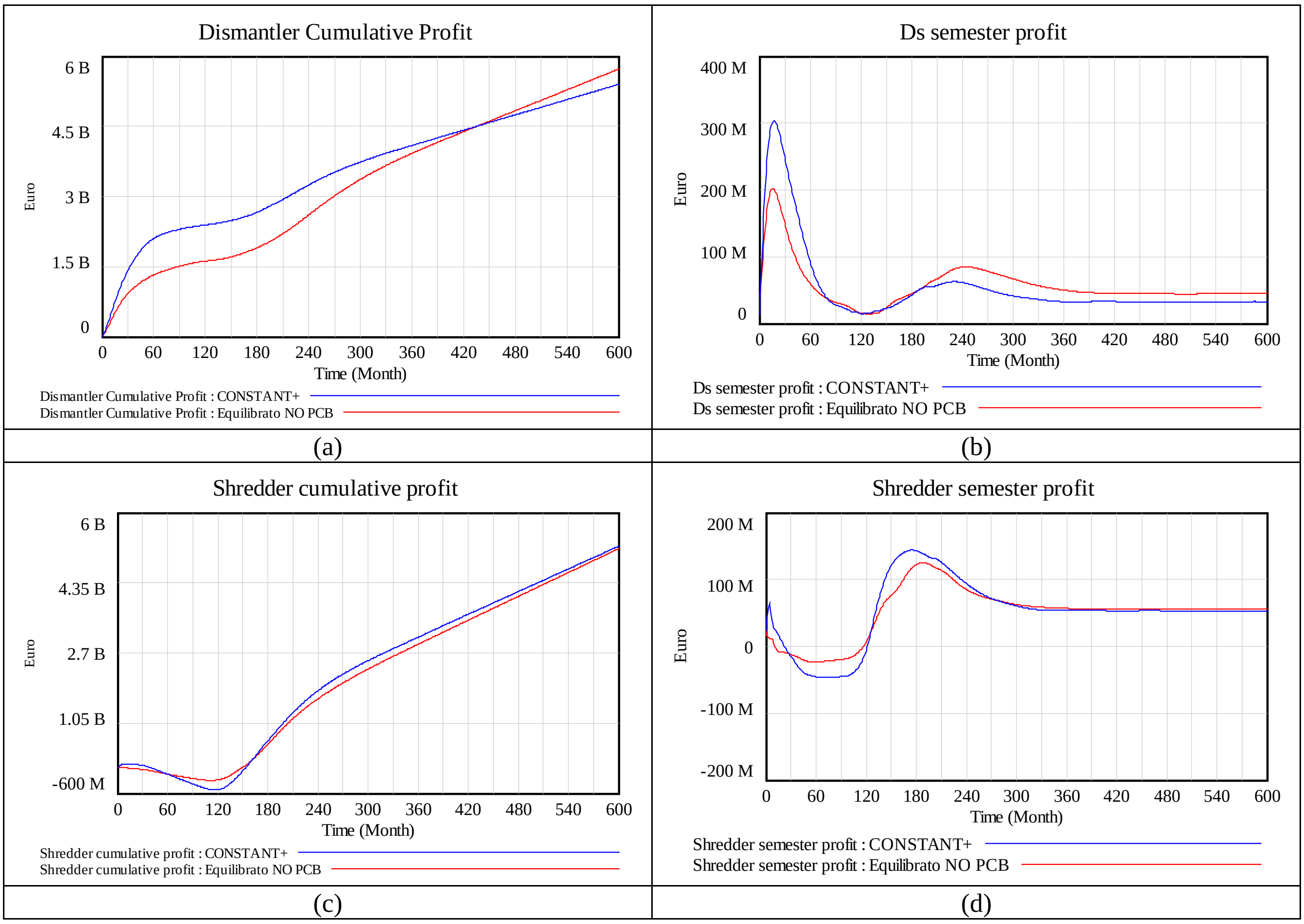

Figure 6. Effect of an increase in constant properties on Sh and Ds profits

5.2.2. Nonferrous prices

One of the other variables potentially influenced by the introduction of automotive electronics recovery in current ELV recovery chains is represented by the nonferrous market price. In this case, with this term the authors refer to all the nonferrous materials present in a car. This way, several metals can be considered within this category, being them basic, critical or precious ones. The intent of the simulation process this time was the assessment of an improvement in the nonferrous market price (going from to current 1.1 Euro/kg to 4 Euro/kg) on the overall economic performance of both dismantlers and shredders. **Figure 7** reports the resulting effects. Also in this case, economic performances of the actors were assessed in terms of cumulative and semester profits. From a dismantler's perspective, an improvement in nonferrous market prices has a relevant effect on the cumulative profit of the entire sector, measurable in 7.5 billion Euros on a period of 50 years (5.8 without automotive electronics). Instead, the effect of this improvement seems to be limited to a certain period (about 10 years) if considering the semester profit. Contrarily to authors' expectations, an improvement in nonferrous marker prices would have an irrelevant effect on shredders economic performances. The cumulative profit of the entire sector will follow, more or less, the same trend. Some more visible effects can be found in terms of semester profits. After some evident under- and overshooting in the first period of time (about 20 years), the system will stabilize at the same level that could be reached without the introduction of automotive electronics recovery processes. However, this equilibrium seems to be not a stable one.

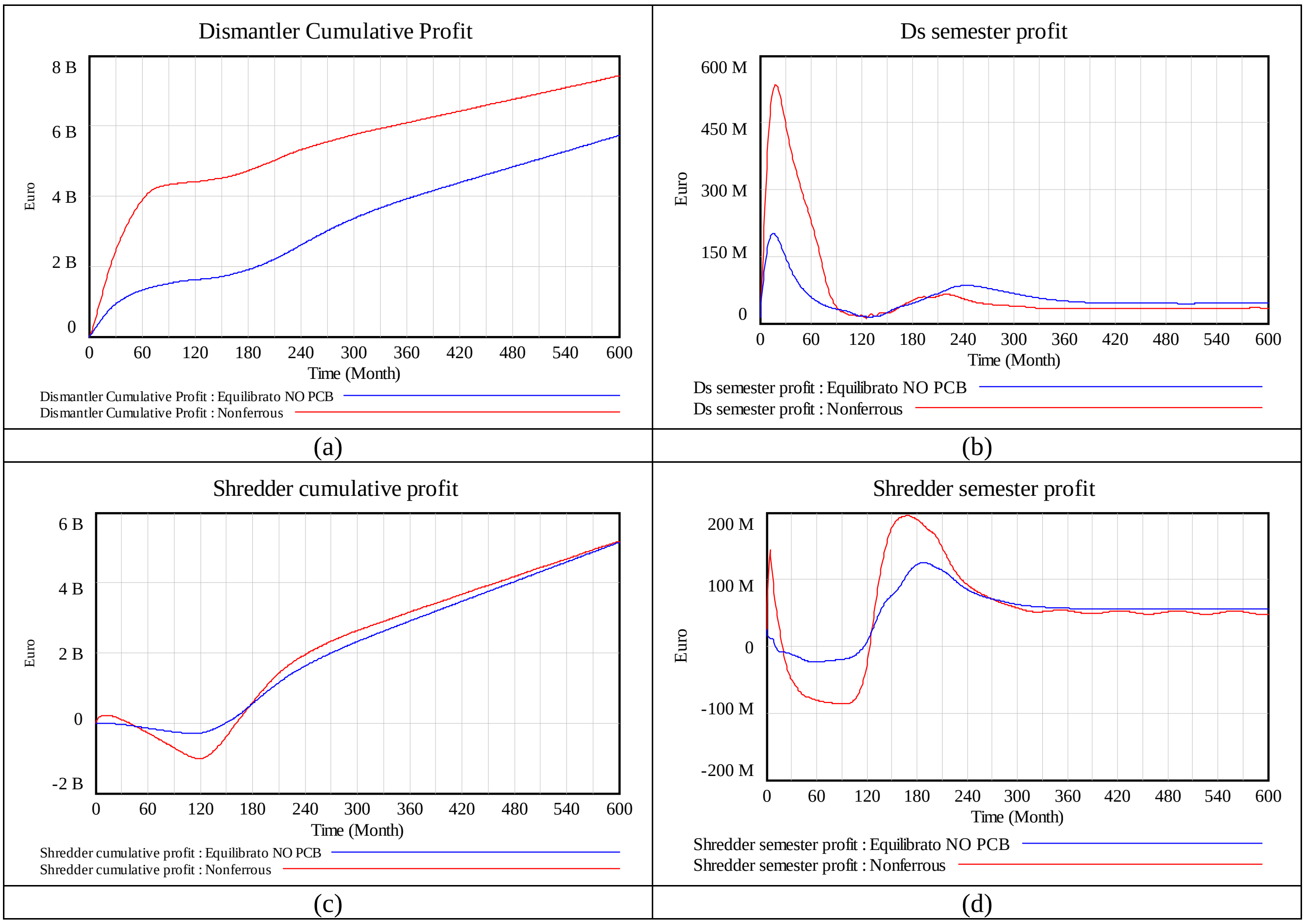

Figure 7. Effect of an increase in nonferrous price on Sh and Ds profits

5.3. Main findings

The previous two sub-sections tried to quantify – theoretically and graphically – the potential economic impact related with the introduction of automotive electronics recovery processes within the current Italian ELV recovery chain. However, nothing was said about both interactions and material flows between dismantlers and shredders. In fact, together with profits, also these last two elements will change, depending on the selected scenario.

From a first side, within a scenario seeing shredders as the main responsible of the new recovery process, their interactions and flows with dismantlers will change considerably. Considering current practices, the addition of a dedicated process focused on automotive electronic components will augment the complexity of the whole industrial system. Dismantlers will be only responsible for the disassembly of electronic components from junk cars, but the level of accuracy of these activities will not be controlled. Their only intent will be the fastest disassembly of electronic components (because of exponential increases of operational costs) and their direct selling to shredders. These last ones (like currently done for ferrous metal scraps) will negotiate with dismantlers about the economic value to be rewarded to them. Then, after the material recovery process, shredders will have to cope with the raw material market, by negotiating the economic value of the recovered materials (like currently done for ferrous metal scraps). This way, new internal drivers influencing transactions will be identified in: (i) scrap electronic components disassembly costs and (ii) scrap electronic components market price (for dismantlers), (iii) scrap electronic components recycling costs and (iv) secondary materials market price (for shredders). Given both the technological and procedural affinity of these new activities in comparison with what already done by shredders, the related risks (e.g. investment risk, operation risk and market risk) have been implicitly hypothesised by the authors as low. This is explicitly confirmed also by several industrial experts in the field (interviewed by the authors during the last years), seeing this scenario as the most realistic and logical one.

From the opposite side, within a scenario seeing dismantlers as the main responsible of the new recovery process, interactions and flows between dismantlers and shredders will continue to be the same like today. The addition of a dedicated process focused on the recovery of automotive electronic components will influence only usual dismantler's activities. Together with the normal disassembly of junk cars, dismantlers will be asked to disassemble electronic components, shred them, refine the obtained materials and sell them to the market. This time, given this last point, disassembly activities are expected to reach a high level of accuracy. However, the intent of dismantlers will have to cope with a trade-off between recovering as many as possible cores and limit exponential increases of operational costs. This will lead to a balance on the overall amount of electronic components that will be really disassembled and recovered from junk cars. Then, after the material recovery process, dismantlers will have to cope with the raw material market, by negotiating the economic value of the recovered materials. This way, new internal drivers influencing transactions will be identified in: (i) scrap electronic components disassembly costs, (ii) scrap electronic components recycling costs and (iii) secondary materials market price (all of them managed by dismantlers). Given the lower technological and procedural affinity of these new activities in comparison with what already done by dismantlers than what evidenced for shredders, the related risks (e.g. investment risk, operation risk and market risk) have been implicitly hypothesised by the authors as higher than the previous scenario. Even if some big Italian dismantling plants already presents little shredding equipments (visited by the authors before writing this article), the raw materials market is only partially familiar to dismantlers. If not properly managed, this point could be a source of inefficiency that could negatively influence the overall economic performance. However, this last scenario represents the best solution for both politicians and national environmental agencies – also taking into account what reported by the German Ministry of the Environment within its 2016-2019 work program (BMUB, 2016).

Taking into account these two views, this work demonstrates how the politician's perspective could allow better economic performances than the industrial one. Considering the previous **Figure 4** and **Figure 5**, important benefits expected from the introduction of automotive electronics recovery processes in current ELV recovery chains can be compared with the ones currently reached. Results – even if contextualized at Italian level and based on several assumptions (see section 5.4 for details) – demonstrate as a scenario seeing dismantlers as main responsible of automotive electronics recovery processes is the most promising one. This way, dismantlers' cumulative profits could reach about 15 billion euros within 2065, 2.5 billion euros more than a scenario seeing shredders as the main actor. However, whatever the scenario is, benefits coming from the management of scrap automotive electronics are visible and measurable in any configuration of the industrial context. Whoever will be the owner of the recovery plant (either shredders or dismantlers), the economic performance is clearly better than the one reachable through current procedures. Just for assuring that these performances could not be reached simply waiting for positive evolutions of the context, **Figure 6** and **Figure 7** compare alternative scenarios, where a change in either car's materials composition or nonferrous market prices will occur and no recovery of automotive electronics will be done by the actors. What it can be deduced from these pictures is that neither materials composition of cars nor an increase in nonferrous market prices could allow to reach the same economic performances like the ones obtained with the introduction of automotive electronics recovery processes. Even after 50 years, these last graphs show that economic performances will be equal to the ones currently obtained by companies.

5.4. Limits of the research

The industrial context taken into account within this paper is characterized by several limitations that must be considered before assessing results coming from the model. Issues related to illegal transfer of cars among nations and lack of official information about automotive electronics recovery trends influence negatively any kind of study on this topic. This way, several hypotheses were considered during the work. Firstly, input volumes of cars entering the ELV recovery chain were represented only by treated volumes (not generated ones). This way, results presented within the work could be even higher if illegal flows could be limited and/or stopped in some way. Secondly, only fixed plants performances were considered. However, there should be the chance to develop mobile plants dedicated to the recovery of automotive electronics that could be cheaper than fixed ones and could expand the activity area of existing ELV recovery chains. Third, costs and revenue structures of both Italian dismantlers and shredders were extrapolated from interviews. Sensitive data were translated in average values and they were adopted in all calculations presented within the paper. The same logic was followed also in defining costs and revenue from automotive electronics recovery. This amount of approximations could negatively influence economic performances. Fourth, all of the economic performances mapped through simulation refer to scenarios where no national subsidies exist (like in reality). Wherever there could be any sort of national subsidy, economic performances could be better than those reported in this paper. It is possible to say the same thing also in terms of both estimated automotive electronic volumes, material market prices, materials purity levels, costs and revenue structures of the actors. All these elements were assessed both through field interviews or literature reviews. This way, they could represent only partially the real state of the industrial context. Just as an example, automotive electronics volumes could be higher than expected. Especially in the last decade, common cars saw a strong augment in electronic components. In addition, hybrid and electric cars are embedding more electronics than common vehicles, without considering auto-guided ones. This consideration allows the reader to comprehend the level of uncertainty influencing this research field.

6. Conclusions

End of life vehicles are re-known by the experts as one of the main sources of secondary raw materials. Even if the ELV recovery chain is an already established industry in Europe, its management strategies remained the same since many decades, completely based on raw materials market prices. However, this way of doing exposed national ELV recovery chains to several market risks, like unpredictable fluctuations of raw materials market prices, uncontrolled illegal transfer of vehicles among nations and the unavoidable evolution of ELVs' materials mix.

Trying to control and partially limit this exposition to materials market risks, experts proposed several prediction and assessment models, by adopting a variety of simulation approaches. However, all of these works were focused on either a specific actor of the ELV recovery chain or a specific issue affecting the industrial context, without taking into account the overall complexity of national ELV recovery chains and key forces at the base of their survival and sustainability.

Trying to solve the literature gap, this paper adopted the SD methodology as reference method for the development of a decision-support tool. By exploiting what already present in literature, an old SD model implemented for the same reason more than twenty years ago by the Massachusetts Institute of Technology was updated and upgraded, before applying it to the Italian context. The updating process interested values of constant inputs of the original SD model, substituted with Italian data coming from both field interviews and the scientific literature. The upgrading process, instead, interested the materials mix taken into account by the original SD model, by considering also the ones coming from the recovery of automotive electronic components (e.g. hazardous, rare and precious metals, rare earths and epoxy resins). Subsequently, current economic performances of the Italian ELV recovery chain were assessed and compared with the ones potentially reachable through the management of automotive electronics. Results – validated by relevant industrial experts – demonstrated how the new approach could potentially increase the economic performance of both dismantlers and shredders of several billion euros, depending on the scenario taken into account.

Future research streams related to the management of automotive electronics could be the assessment of recycling issues coming from the treatment of hybrid and full-electric cars or auto-guided vehicles. Together with technical issues, also economic, environmental and political ones could be a good ground for future researches and projects. Again, the reduction of information asymmetry among the actors involved in the ELV recovery chain is another element of discussion. Finally, it is of utmost importance to deliver methodologies and technologies improving the sustainability level of enterprises involved in any kind of reverse logistic chain. These methodologies and technologies should be focused on a better integration of reverse logistic chains.

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