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System Dynamics Model for Sustainability Analysis of Mobile Phone Reverse Logistics

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Abstract

E-waste currently represents a portion of global waste problem; nevertheless, e-waste quantities are continuously fast rising all over the world. As the waste problem increases, new business opportunities related to their reuse and recycling could be evaluated. The paper focuses on a particular type of e-waste: mobile phones as they are the most ubiquitous electronic equipment. By analysing market trend in developed countries, mobile phones are characterized by a short life-cycle even if they are still working. Thus, reuse and recycling markets are developing for these products. Their small size is contributing to increase the overall profitability of these secondary market. The aim of this study is to develop a system dynamics model for evaluating sustainability performance of mobile phone reverse logistics. All End-of-Life (EoL) alternatives - starting from the reuse "as is" of the mobile phones to refurbishment, components reuse, materials recycling, and final disposal - have been introduced in the reverse chain. Next, a simulation model has been developed in order to assess the three traditional dimensions of sustainability i.e. environmental, economic and social levels. Two different strategies - a "push" and a "pull" approach - for optimizing the reverse chain have been compared by the simulation model. In the first scenario, the demand of primary market - i.e. upstream tier – enforces reverse chain performances as target levels for each EoL options have been fixed a priori. On the other hand, the "pull" logic works with feedbacks in the second scenario, such as the performance of each upstream tier in the chain depends on dynamics applied on the downstream tiers, i.e. the sustainability dimensions. The scenario analysis has been applied in an illustrative example.

1 Introduction

Huge problem of traditional waste management has been recently increased by the increasing of new waste flows due to technological innovation – the so called Waste Electric and Electronic Equipment (WEEE) or E-waste - are quickly increasing all over the world. Even if E-waste management is a small portion of global waste contributing only from 0,01 % to 3 % of the total global waste quantity; on the other hand, its rate is growing two to three times faster than any other waste stream (SBI Energy, 2011). Furthermore, consumer consciousness for more green products is increasing also in this sector (Balboa, 2011). Thus, the increasing quantity of WEEE together with both the complexity of treatment mainly due to dangerous substances (such as mercury, cadmium, chrome) and the different EoL (End-of-Life) options contribute to increase the complexity of this reverse supply chain. Moreover, different type of products generate WEEE: from household appliances (or "white goods") to small equipment. The focus of this study is on mobile phones: they are the most widely used electronic devices in the world and their life cycle is now diminishing due to the speed of technology innovation. Thus, differently from household appliance such as refrigerators or washing machines, mobile phones are often substituted due to technological obsolesce more than a breakdown. This issue causes re-use option in reverse logistics chain could be easily adopted for mobile phones compared to other WEEE flows (Ongondo and Williams, 2011). Furthermore, re-use option will work effectively if a secondary market is full developed; thus, the whole sustainability level of this reverse chain could increase. The aim of this paper is to assess sustainability performance of mobile phones EoL management by comparing different strategies of managing the reverse chain. The paper is organized as follows: critical factors in EoL management of mobile phones are analysed in section 2; next, the proposed approach for assessing sustainability performance of this reverse logistics chain is described in section 3.

2 End-of-Life Management of Mobile Phones

A typical reverse chain started from final customer: three main phases could be outlined for mobile phone reverse chain which is listed following:

1) collection phase;
2) assessment phase. Two are the basic alternatives to disposal for used mobile phones: reuse and recycle;
3) processing phase.

Starting from *collection phase*, it could be carried out in different ways. Final user deliveries at a collection point its mobile phones in the drop-off option. Usually, bins could be located in the street; for mobile phones, the most suitable alternative for localization is in a shop (or mall) as they have a residual economic value. One collection method applied in this case is the e-business service*:* companies through their websites are now developing innovative services as the firm pays used mobile phones according to their quotations. Another collection method is carried out by Non-Governmental Organizations (NGOs): they organize events or promote campaigns for collection used mobile phones. The main purpose is not just economic as they aim to safeguard the environment by avoiding the incorrect disposal of cell phones, and to raise funds for humanitarian scopes. These events are sometimes organized by the local authorities such as municipalities or commercial entities.
After collection, used phones are inspected in order to asses a potential market demand i.e. *the assessment phase*. One of the major critical factor is the residual value. Basically, the residual value is determined by the age, the model type and its actual condition. New and fashionable products with up-to-date technology but also phones that are working usually retain an economic value for the used device market. In detail, three main options could be carried out for mobile phone re-use (Neira et al., 2006):

- refurbishment at product level;
- reuse "as is" at product level;
- reuse at component level.

Refurbished phones are used equipment where not-functional devices have been replaced with new one: main cases are damaged or worn electronic components (e.g. batteries), formatting (usually by replacing the motherboard, the main circuit of the telephone) and updating software to the latest version. Moreover, re-used (or second-hand) mobile phones are equipment sold "as is" as only a control activity has been performed. Finally, recovered parts are used to repair or refurbish the same or similar models or for products different from cell phones, such as memory devices in toys. Mobile phones recycling consists mainly of material recovery such as plastic, copper and precious metals (gold, silver, palladium). The reuse of used mobile phones has been asserting for several years in Anglo-Saxon countries mainly because there is a "culture of second-hand goods" not so widespread in other parts of developed countries. In the USA, half of used phones are sold in the national territory and the strategy of renovation and resale of used equipment is followed by various firms**.** Instead, in Italy, used cell phone business is still in the initial phase, reflecting the poor maturity of reuse and recovery actions.

3 A Sustainability Analysis of WEEE Management

The need to reconcile the economic growth with an equitable distribution of resources in a new model of development paved the way since the '70s, when it was mature the idea that the classic concept of development, linked exclusively to the economic growth would determine the collapse of natural systems in the short term.
According the World Commission on Environment and Development (UN, 1987), a worldwide sustainable development growth has to be designed by satisfying the needs of the present generation without compromising the ability of future generations to meet theirs. The basic principle is the inter-generational equity: the future generations have the same rights of the current population. This concept may also be extended to intra-generational level: within the same generation, people from different economic, political, social and geographical realities have the same rights. Therefore, in this perspective, sustainability must be intended as a continuous process invoking the need to combine the three fundamental and inseparable dimensions of development: environmental, economic and social: the so called "Triple Bottom Line" (3BL) strategy. Environmental sustainability means the ability to preserve over time the three functions of environment: supplier of resources, receptor of waste and direct source of utility. On the other hand, the economic sustainability is the capacity of a system to generate a lasting growth of economic indicators, particularly income and employment. The social sustainability usually refers to the capacity to ensure conditions of human wellbeing (i.e. safety, health, and education) equally distributed by class and gender. These concepts are starting to be applied in the municipal waste management context. Morrissey and Browne (2004) revised approaches applied for designing waste management systems and how could be applied for efficiently integrating 3BL approaches. Masaru (2007) critically analysed by a technical and organizational point of view environmental impacts derived from waste management systems. Seadon (2010) analysed by a strategic point of view critical features characterizing a sustainable waste management system. The importance of feedback (both positive and negative) loops have been outlined together with the requirements of an efficient information flow management. Wagner (2011) reviewed the critical problem of integrating conflicting objectives in sustainable waste

management systems: landfilling treatments were analysed as an illustrative example. Bijl (2011) recently analysed also impacts due to waste management system on the social dimension of sustainability. Georgiadis and Besiou (2009) studied the environmental and economical sustainability of WEEE closed loop supply chains with recycling through a system dynamics analysis. Their starting point was the observation that the worldwide production of electrical and electronic equipment was increasing, reducing both resources and landfills. They investigated the significance of the factors that comprise the environmental sustainability strategies (environmental legislation and green image) and the operational features of the closed loop supply chain (chain's features, products' features and economic parameters), their interactions and the type of their impact on the environmental (availability of natural resources and landfill availability) and economical sustainability of a WEEE closed loop supply chain. They used an extension of a system dynamics model of a closed loop supply chain with recycling activities introduced previously, providing a system dynamic model which incorporates both the environmental and the economical dimensions of sustainability and comprising a broader number of characteristics in describing the environmental sustainability strategies and the operational features of the supply chain. The developed model was validated using data from a real world closed loop supply chain of EEE in Greece. Extended numerical investigation provides insights to the managers and the legislators with regard to the actions which can lead to sustainability.

After this brief review, waste management systems regarding mobile phones has been analyzed by applying a closed loop supply chain point of view. Guide and Vassenhove (2008) define the closed loop supply chain as the design, control and operation of a system to maximize value creation over the entire life-cycle of a product with dynamic recovery of value from different types and volumes of returns over time. Two main streams may be identified in this reverse chain: the physical flow (of materials in process, products or services) from supplier to customer and the information flow in the opposite direction. Also the return of products, materials recycling and disposal, typical of the reverse supply chain, are parts of the physical flow. According to this perspective, the mobile phone EoL management has been critically analysed; a schema is depicted in figure 1. The direct channel represents the production system with the traditional activities (i.e. supplying, production, distribution and sale); the reverse channel starts with the collection of used mobile phones; moreover, all possible alternatives for EoL management have been assessed. Three main options have been evaluated: reuse (reuse of mobile phones “as is”, refurbishment and components reuse), recycling and disposal.

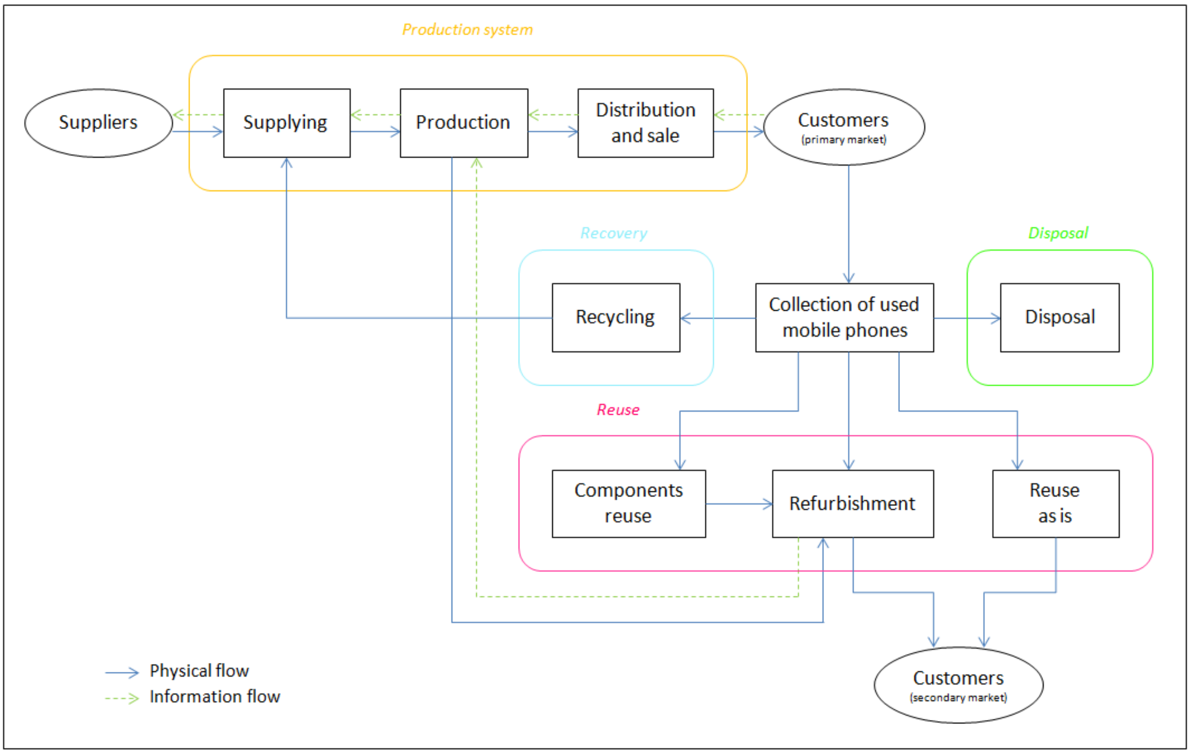

Figure 1: The reverse chain in EoL of mobile phones

In brief, suppliers provide raw materials needed for production. The produced mobile phones are distributed and sold to customers. The demand of primary market causes the functioning of direct channel; next, mobile phones

production is organized by a manufacturing point of view. The reverse chain starts at customer level: a portion of used phones is delivered to collection points or sold to companies purchasing the used equipment by the web sites or they are delivered to the retailer where the new phone has been bought. In the European area, the retailer usually must withdraw second-hand items if customer buys new one. Usually, a huge quantity of used mobile phones is still in use or not delivered to the waste management system. The collected equipment - depending on their value – could be sold in the secondary market after being refurbished. Thus, while in the direct channel it's the market demand "pulling" the production system, in the reverse channel the products are "pushed" in the secondary market. During the refurbishment process, not working components of mobile phones are substituted with reusable components if they are available, otherwise with new components. If reuse is excluded for a used mobile phone, recycling can be considered. In this case, the materials recovered from equipment are raw materials usable in production process. The supply chain is therefore closed. The option disposal has been taken into consideration for those phones that should not be recycled.
In this supply chain, environmental sustainability may be assessed in terms of:

- use of natural resources,
- quantity of waste to be disposed of,
- protection and preservation of the environment.

The indicators are respectively the level of both *natural resources use* and *emissions of carbon dioxide,* and the *quantity of mobile phones disposed*. Assuming that these indicators must make a positive contribution to sustainability, they become saved natural resources, quantity of mobile phones not disposed in landfill and saved emissions of carbon dioxide. According to the economic dimension, performance of reuse and recovery of used mobile phones has to be compared with manufacturing new phones and providing for disposal the collected ones; thus, an indicator (i.e. total *profit from used phones*) has been introduced to assess profits from this second-hand market. The concept of social sustainability underlines the equity in the distribution of welfare. Therefore it may be assessed in terms of *access to mobile phones* by the population with an indicator measuring the number of persons who, thanks to the secondary market, can possess tools and technologies that otherwise they could not afford. Estimated impacts together with proposed indicators are in table 1.

Table 1: Sustainability indicators

Sustainability dimension	**Estimated Impact**	***Indicators***
Environmental	Use of natural resources	Amount of saved natural resources (*saved materials*)
Environmental	Waste quantity disposed	Amount of mobile phones not disposed (*not disposed waste*)
Environmental	Protection and preservation of the environment	*Saved CO_2 emissions*
Economic	Profit	*Profit of new mobile phones,* *Profit of mobile phones reused as is,* *Profit of refurbished mobile phones,* *Profit of recycled mobile phones,* *Profit of disposed mobile phones.*
Social	Accessibility to mobile phones	Number of persons who, thanks to secondary market, can buy mobile phones (*new users*)

4 The Proposed System Dynamics Model

System dynamics approach has been applied for assessing the sustainability performance of mobile phone EoL management. Basic elements are causal loop diagrams, stock and flow diagrams and auxiliaries variables. Causal loop diagrams are an important tool for representing the feedback structure of systems. They consist of variables connected by arrows denoting the causal influences among the variables. Stock and flow diagrams are tools for assessing variable dynamics through a period; auxiliaries consist of functions of stocks (and constants or exogenous inputs). Starting from the supply chain structure previously proposed, causal loop diagrams have been developed; main parts are described as follows in detail.

Raw material supplying: The entity *raw materials* is split into natural resources and recycled raw materials in order to distinguish natural from recycled materials. The *demand of primary market* determines the *amount of raw materials needed for production (supply rate).* Between these two variables there is a positive causal link because when demand increases, the amount of materials needed to produce mobile phones increases. There is the same causal link between the *amount of raw materials needed for production* and the supply rates. If the *supply rate of natural resources* increases, the available amount of these resources decreases. The same reasoning is valid for recycled raw materials. The amount of recycled raw materials depends on the materials recovered during the recycling process. An increase in *recycled materials* results in an increase of the *availability of recycled raw materials*. As the purpose is to build a supply chain model respecting the environment, the logic underlying the supply process is that recycled materials are used as much as possible in order to conserve the natural resources. Obviously, as long as they are available. So, if there are more recycled raw materials, there is an increase in their supply rate and then, as a consequence, the supply rate of natural resources decreases. From the diagram it's possible to note that a balancing loop is created between the variables *availability of recycled raw materials* and *supply rate of recycled raw materials*.

Production system: the information flow of supply chain direct channel consists of a series of positive causal links. With the increasing of the *demand of primary market*, the number of *produced mobile phones* increases. With the increasing of the number of phones to be produced, the *amount of raw materials needed for* their *production* increases. Being positive causal links, if the variable representing the cause decreases, also the variable representing the effect decreases.

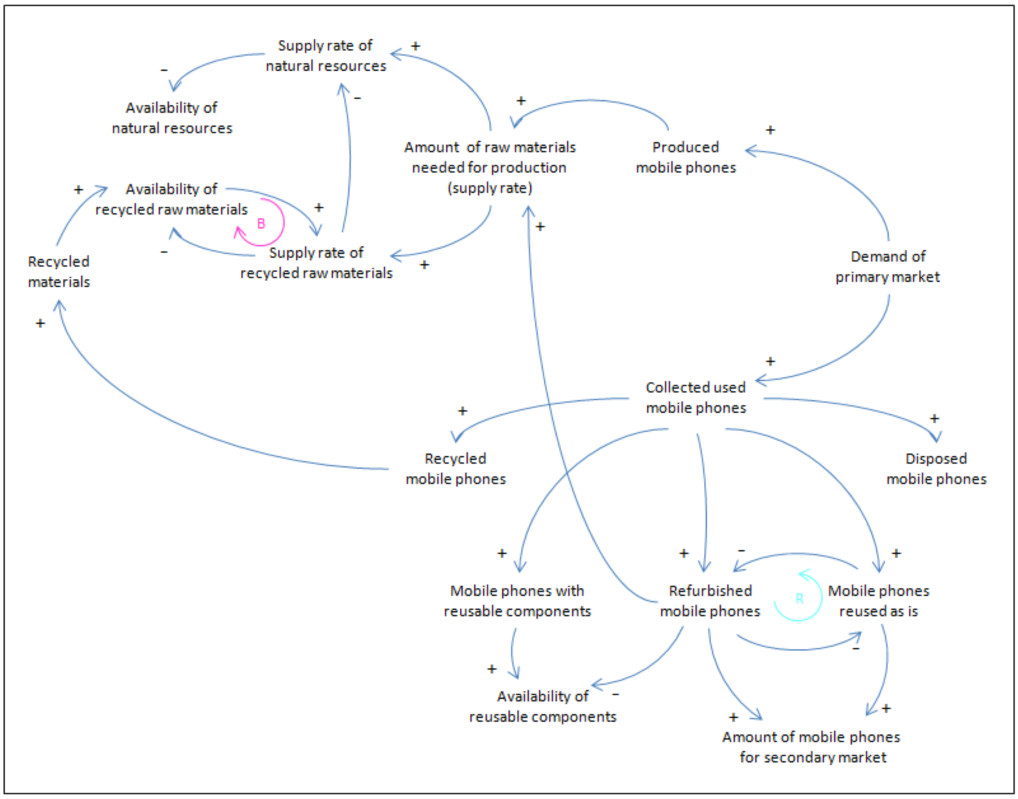

Figure 2: The proposed causal loop diagram

EoL tiers: the number of *collected used mobile phones* depends on how many new mobile phones are bought and then the market demand. Between the *demand of primary market* and *collected used mobile phones* there is a positive causal link. There is the same link between the collected phones and the different alternatives for End-of-Life equipment. Since the reusable components are installed on refurbished phones, with the increasing of refurbished equipment, the available amount of reusable components decreases. The variables representing the different alternatives for used phones are connected by negative links because, stated the number of collected mobile phones, when the phones managed in a way increase, those managed in other ways diminish. Therefore, for each pair of variables, a reinforcing loop is created. To enhance the visibility of the diagram, the loop has been represented only for a pair of variables.

The three causal loop diagrams have been put together (figure 2), connecting them through the positive causal links between *recycled mobile phones* and *recycled materials* and between *refurbished mobile phones* and the *amount of raw materials needed for production*. In order to construct stock and flow diagrams, it is necessary to transform the variables of causal loop diagrams into stocks and flows, keeping in mind the links between them and their polarity. At first the direct supply chain is taken into consideration and then the reverse one. The raw materials, such as natural resources and recycled raw materials, and the produced mobile phones may be considered stocks as they are entities accumulating and depleting over time. These entities are connected by flows regulating the accumulation and depletion of stocks over time. The flow *sale* ends in a stock outside the boundary of the system and for this reason, it is represented by a cloud. Also the natural resources are considered outside the system. The *demand of primary market*, as external input determining the production, is an auxiliary variable. In the reverse supply chain, the variables representable as stocks are: *collected used mobile phones*, *mobile phones reusable as are*, *refurbished mobile phones*, *mobile phones with reusable components*, *recycled mobile phones and disposed mobile phones.* The *collection rate* is linked to the *demand of primary market* and the origin of this flow is external to the system. As for causal loop diagrams, also stock and flow diagrams are joint to have an overview of the entire supply chain. The causal links between *refurbishment rate* and *production* and between *recycling rate* and *recycled raw materials* are added. Between these two last stocks, the auxiliary variable *recycled materials*, function of *recycled mobile phones*, is inserted.

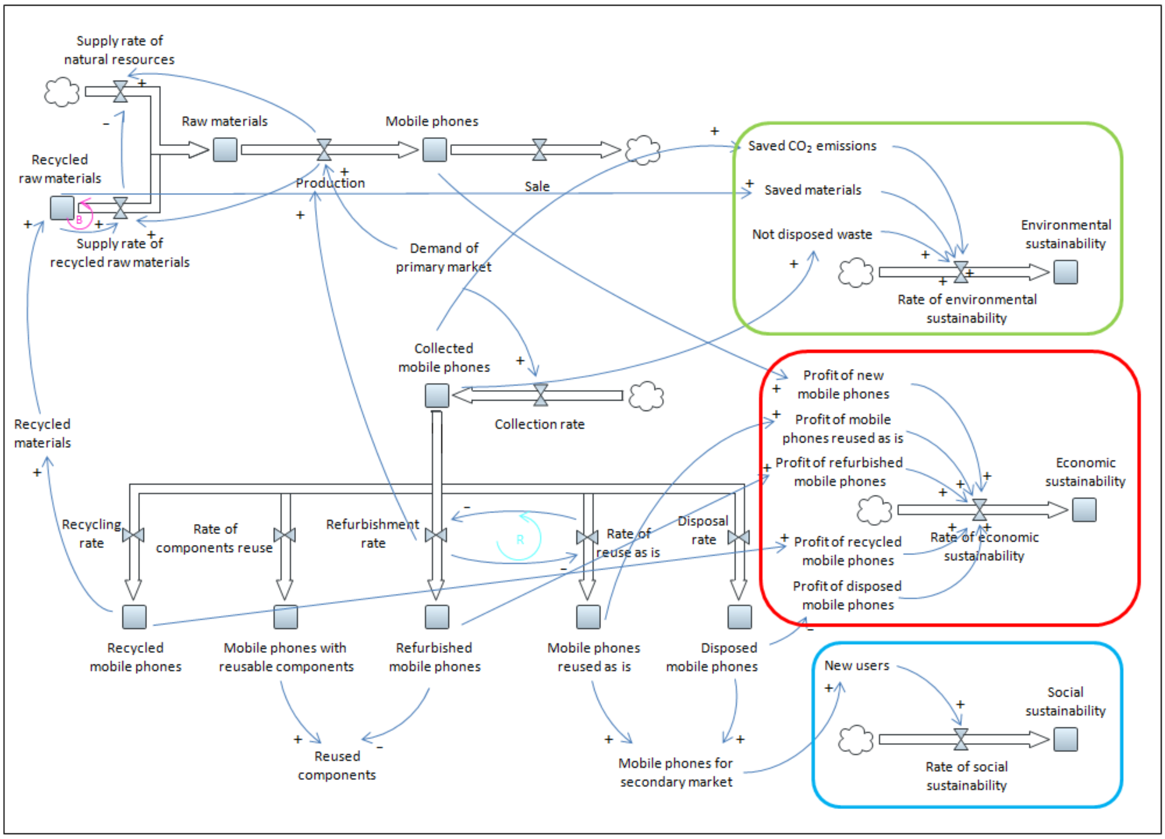

Figure 3: Closed loop supply chain with sustainability – stock and flow diagram

Sustainability has to be evaluated using the model. Therefore it is necessary to integrate in stock and flow diagram of closed loop supply chain stocks, flows and auxiliary variables through which it's possible to measure the achieved levels of sustainability. The three dimensions of sustainability can be represented through some stocks since they are entities accumulating over time through a flow defined by the indicators. Then the indicators must be connected with the components of the model which they depend on (figure 3).

5 The Simulation Analysis

5.1 The model hypothesis

The system dynamics model proposed in the previous section has been developed by a software tool AnyLogic ® 6.0. Main hypothesis evaluated in the simulation model are reported as follows:

- the demand of primary market is constant; thus, the rate for collected used phones has been estimated as 50%;

- mobile phone flows in the reverse chain have been fixed: 20% is reused as is, 30% is refurbished, 15% falls into the category of cell phones whose components are reused; 30% is recycled, 5% is disposed;
- all reusable components are installed in refurbished mobile phones;
- for every refurbished mobile phone, each raw material requirement for the production is increased by 10% to take account of the new components installed on them;
- batteries are not recycled;
- average quantities of recovered material from a mobile phone are plastic (48 g), copper (15,66 g), gold (0,04 g), silver (0,42 g), palladium (0,02 g).

Next, an illustrative example is described about one well known mobile phone, the iPhone 3G 16 GB. Its annual demand of Italian primary market has been estimated at approximately 180.000 units of mobile phones and the indicators of economic sustainability are:

- profit of new mobile phone = 428 €,
- profit of mobile phone reused as is = 149 €,
- profit of refurbished mobile phone = 315 €,
- profit of recycled mobile phone = 1,61 €,
- profit of disposed mobile phone = - 0,58 €.

5.2 The scenario analysis

After implementing the model in AnyLogic, two strategic scenarios for managing the reverse chain have been analysed. In the first scenario, that will be the baseline scenario which the others will be compared to, it’s the demand of the primary market, i.e. the upstream level, which determines the performances of reverse supply chain. The logic of the supply chain management is defined "push" because the different rates are fixed in advance (of collection, reuse “as is”, refurbishment, reuse of components, recycling, disposal) and the results obtained in terms of sustainability depend on the assigned values. In the second scenario, however, the performances of each upstream tier in the supply chain depend on the dynamics applied downstream. In this case the management logic is called a "pull" because the sustainability levels to be achieved every year are imposed and with feedback the adaptations of various rates are obtained making possible the achievement of predetermined levels of sustainability. The sustainability dimension will be taken into account, but first the environmental and then the economic one. Time interval of simulation (5 years), annual demand of primary market (180.000 mobile phones), fractions of recycled, reused as is, refurbished and disposed mobile phones and fractions of recovered materials are data common between the two scenarios.

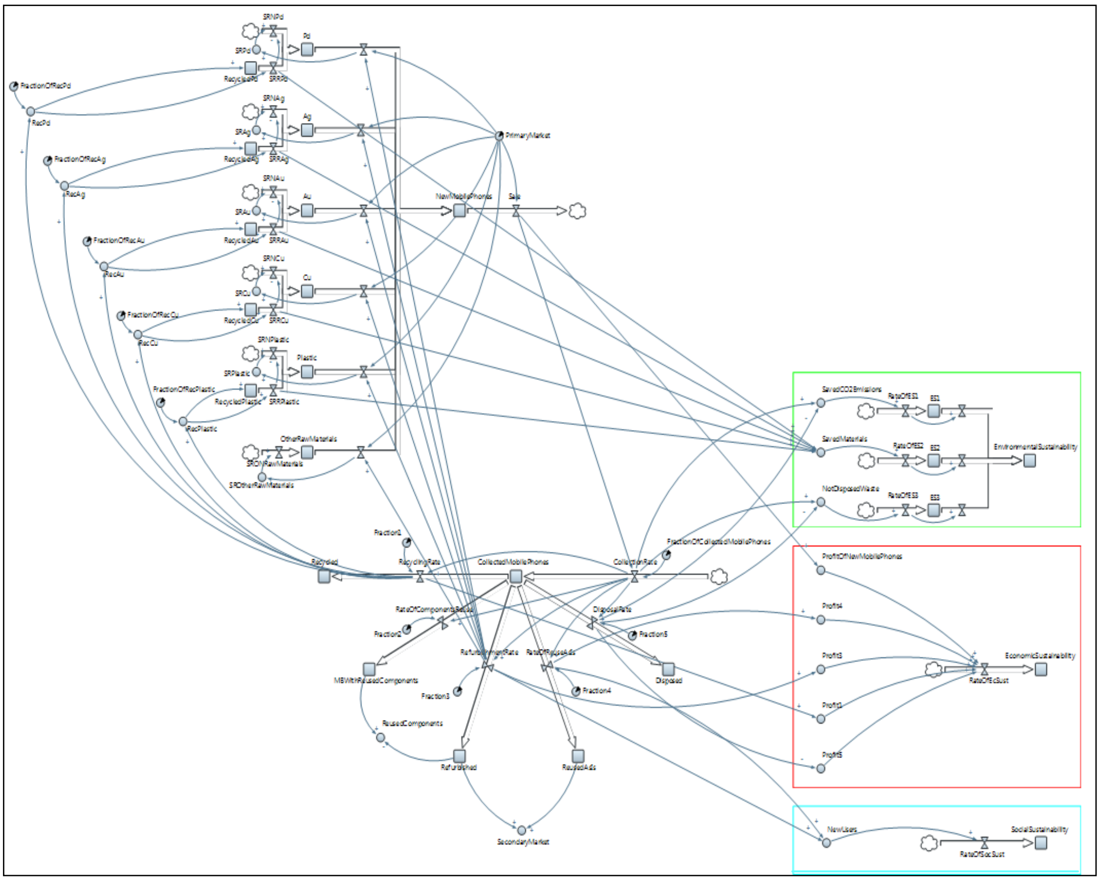

Figure 4: The model in AnyLogic

The "Push logic", scenario 1: the first scenario consists of the simulation model implemented in AnyLogic and it allows to see the results achieved in terms of sustainability when the system works according to the initial hypothesis. Since the demand is constant (therefore it has the same value every year) and the collected phones are always equal to 50% of those new sold, also the various rates are constant and each year they accumulate the same amount in the stocks they feed.

The "Pull logic", scenario 2: the second scenario derives from the first one, but it is focused on environmental and economic performances of the whole supply chain which are fixed by a priori values.
Thus, if the sustainability level is different from the target, all inflow variables have to vary. Two sub-scenarios have been also assessed: one focusing on environmental (scenario 2A) and one on economic dimension (scenario 2B).

Scenario 2A: it is necessary to act on its inflow to increase the stock of environmental sustainability. The values to be taken by the flow were established taking into account the annual value of stock inflow in the previous scenario, 1.198.732, and increasing it by 10% per year for each year subsequent to the first.
Scenario 2B: it is necessary to act on its inflow to increase the stock of economic sustainability. Its values were established taking into account the annual value of the stock inflow in the first scenario, 88.267.860, and increasing it by 2% per year for each year subsequent to the first.

In both scenarios, set the value of the demand of primary market, the variable contributing to determine the inflow of the considered stock and consequently influencing the achieved levels of sustainability is the *fraction of collected mobile phones*. Table 2 shows the values it takes in order to achieve the goals.

Table 2: Values of fraction of collected mobile phones in scenarios 2A e 2B

Scenario	**Value of *fraction of collected mobile phones*** (percentage of new sold mobile phones)				
	1st year	**2nd year**	**3rd year**	**4th year**	**5th year**
2A	50%	55%	60,5%	65,5%	73,2%
2B	50%	57,9%	65,9%	74,1%	82,4%

In the scenario 2A, *fraction of collected mobile phones* goes from 50% (first year) to 73,2% (fifth year). In the scenario 2B, it goes from 50% (first year) to 82,4% (fifth year).
The results obtained using the simulator (table 3) show that:

- in the scenario 2A, the environmental sustainability increases by 22,1%, the economic sustainability increases by 2,8% and the social sustainability increases by 22,1% compared to the first scenario (these percentages were obtained by comparing the stock values in the two scenarios at the end of the reference period;
- in the scenario 2B, the economic sustainability increases by 4,1%, the environmental sustainability increases by 32,1% and the social sustainability increases by 32,1% compared to the first scenario.

You can notice that when the fraction of collected mobile phones increases, environmental and social sustainability grow more than the economic one.

Table 3: Value obtained in the different scenarios

Element	**Value (5th year)**		
	Scenario 1	**Scenario 2A**	**Scenario 2B**
Fraction of collected mobile phones (*percentage of new sold mobile phones*)	50 %	73,2%	82,4%
Saved CO_2 emissions (*kg*)	5.557.500	6.785.819	7.340.415
Saved materials (*kg*)	8.659	10.573	11.437
Not disposed waste	427.500	521.986	564.647
Environmental sustainability (*score point*)	5.993.659	7.318.258	7.916.311
Economic sustainability (€)	441.339.300	453.746.085	459.347.723
Social Sustainability (*new users*)	225.000	274.727	297.176

6. Conclusions

Verified the need for our planet welfare to reduce the amount of waste to be disposed of and the emissions of harmful gases into the atmosphere resulting from production processes and to conserve natural resources, the scientific community agrees to support the potentialities of waste reuse and recycling. Alongside the problem of "traditional" waste management, recently, the problem of WEEE management arose too. The increase of electronic product purchasing is driven by the accelerated pace of obsolescence in the electronic goods sector. With it, e-waste recycling and reuse services market is growing worldwide. Mobile phones are the most used electronic products on the globe and those ones more frequently changed. And it is precisely the value they retain to make their reuse and recycling a valuable investment. Recently, several business examples have showed that mobile phone reuse and recycling can be interesting opportunities for companies all over the world. Moreover, product reuse is one primary option in order to improve environmental and social sustainability of e-waste management.

A model for the evaluation of mobile phone reverse logistics through an integrated analysis of the entire supply chain has been proposed in this study. The proposed approach is based on system dynamics theory aiming to assess effectively feedback loops characterizing reverse chains. The simulation model allows to estimate the results obtainable at a given time interval under certain assumptions or to determine what are the variables influencing the achievement of certain objectives and the values they should take. The whole system depends on the demand of primary market; set this value, the variable influencing the achieved levels of sustainability is the amount of collected used mobile phones. The model simulation in various scenarios shows that economic sustainability is the dimension growing less when the amount of collected mobile phones increases. Future developments will be directed to apply the proposed approach to different WEEE supply chains.

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