# Modeling Reverse Logistics Networks: A Case Study for E-Waste Management Policy

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**Abstract.** Reverse Logistics (RL) groups the activities involved in the return flows of products at the end of their economic life cycle. Enterprises and policy makers all over the world are currently researching, designing and putting in place strategies to recover and recycle products and raw materials, both for the benefit of the environment and to increase profits. However, the management of return flows is complex and unpredictable because consumer behavior introduces uncertainties in timing, quantity, and quality of the end-of-life products. To proactively cope with these concerns, we propose a metamodel that serves as a foundation for a domain specific modeling language (DSML) to understand RL processes and apply analysis techniques. This DSML can also be used to examine aspects such as RL strategies, capacity of the facilities, and incentives (e.g., sanctions and tax reliefs introduced by regulators). The core element of this approach is an extensible metamodel which can be used for analyzing specific applications of RL such as E-waste management.

**Keywords:** Reverse Logistics · Metamodel · DSML · E-waste management

## 1 Introduction

In a supply chain (SC), reverse flows consist of products at the end of their life cycle (EOL), or products that have been returned at other stages in the forward SC. The logistics of these flows, known as Reverse Logistics (RL), is formally defined as "the process of planning, implementing and controlling flows of raw materials, in-process inventory, and finished goods, from a manufacturing, distribution, or use point to a point of recovery or point of proper disposal" [15]. Growing concerns derived from global competitiveness, higher customer expectations, and superior SC performance have made RL all the more relevant. Lambert et al. [10] found that RL issues have been divided into three main concerns: recovery/distribution, production and inventory, and SC management. In all of these, quantitative and qualitative analysis techniques are used, together with approaches such as case studies, literature reviews, and conceptual descriptions. More recently, Suyabatmaz et al. [18] conclude that due to the high complexity and heterogeneity of reverse flows, problem-specific methodologies as well as generalized models are required and call for research efforts to study RL issues by


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incorporating analytical and simulation models. In particular, methods are noticeably needed to improve RL capabilities and to fulfill needs over short- or long-time periods.

Thus, a need has been identified for systematic approaches to understand, design and deal with the uncertainty of reverse flows along a SC and to reduce their increasing environmental impact. Along these lines, research has been conducted in specific industries such as in bottled products [9] and mobile phones [14]. Nowadays, RL scenarios involving E-waste management-i.e., electronic components that are considered obsolete or no longer functioning - are of particular interest: it contains valuable materials that should be recovered, as well as hazardous substances that require special handling to minimize pollution concerns. In addition, the increasing number of products containing electronic components have made this the fastest growing global waste stream. The Global E-waste Monitor 2017 has estimated that worldwide a staggering 44.7 million metric tons (Mt) of E-waste was generated in 2016, equal to 6.1 kilograms per inhabitant (kg/inh) annually. It has also predicted an alarming increase to 52.2 Mt alike to 6.8 kg/inh, by 2021 [3]. All of this has made imperative to design, implement, measure and improve strategies and public policies involving RL activities for E-waste management.

In order to proactively cope with these growing concerns on RL, we built a proposal to allow researchers, practitioners and decision makers to analyze, understand, and perform experiments with short- or long-term scenarios. In particular, we enable the exploration of "what-if" scenarios in RL networks with respect to costs, quality and sustainability outcomes. The core of this work is an extensible Domain Specific Modeling Language (DSML) [7] to create RL scenarios for analysis purposes. The language is built on top of a RL metamodel, product of a thorough literature review, capturing the fundamental RL concepts and relations that enable modeling the entire process.

This paper focuses on the modeling aspects of the metamodel for the RL process. The remaining sections are organized as follows: Sect. 2 presents a brief overview of RL providing a context for the rest of the work. Sections 3, 4 and 5 present our overall approach and details the construction and structure of the RL metamodel. Particularly, Sect. 5 illustrates its usage, by creating a scenario based on the recently promulgated laws for E-waste management in Colombia. Section 6 discusses how the metamodel can be extended to support dynamic analysis methods such as system dynamics (SD); and in Sect. 7, we draw initial conclusions, and future research avenues.

## 2 A Brief Reverse Logistics Background

This section focuses on presenting an overview of RL: its definition, main differences with forward logistics, and current streams of research. While forward logistics refers to the flow of a product from the manufacturer to the end consumer, Reverse Logistics is the process in which goods are recovered from an end point in order to either recapture value or to properly dispose them. Compared to forward logistics, the management of these flows is highly complex and less predictable because consumer behavior introduces uncertainties in timing, quantity, and quality of the EOL products [6]. As stated by Suyabatmaz et al. [18], reverse flows are complex and heterogeneous, and its study requires problem-specific methodologies as well as generalized models.

There are three main forces driving current work on RL: regulations, economic factors, and consumer awareness [4]. There is also an emerging trend which includes sustainability, and has adopted analysis techniques such as SD [8]. Current industry efforts to tackle reverse logistics issues include, for example, the Supply Chain Operations Reference (SCOR) [17], which provides a detailed description of the activities and the possible indicators that can be measured. However, the SCOR scope regarding RL is very limited and cannot model the behavior of the full reverse chain. While these initiatives have recognized the importance of putting in place a proactive strategy for RL, the management of return flows is easier said than done. The design and analysis of RL networks is a topic that is far from settled and offers a great number of opportunities. Likewise, the conceptual structure of the field is not yet fully established: there are some key concepts that are shared by most approaches and have well accepted definitions, yet there are also concepts that are included in only a small number of works and have definitions that are vague or even contradictory. Therefore, there is a need to further standardize the elements, definitions and relationships in the domain.

## 3 A Model-Based Approach to Understand Reverse Logistics

The proposal to support the understanding and analysis of RL networks is based on three main ideas that can be illustrated through phases (see Fig. 1). The first one is creating a metamodel for the RL domain. The second phase is to extend and refine said metamodel in order to adapt it to the needs of specific scenarios. This is because distinct scenarios can have particular requirements depending on the product entailed in the RL process and the specific country of analysis (e.g., E-waste management in Colombia). The third phase further extends the metamodel with new concepts, attributes and relations that depend on the type of analysis that is intended to be applied to modeled scenarios (e.g., SD, discrete event simulation). This metamodel is crucial in the construction of a subsequent RL DSL.

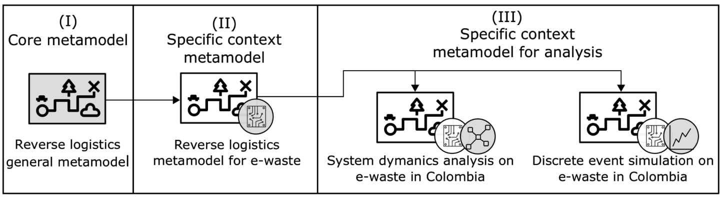


**Fig. 1.** General approach for RL modeling

Section 4 describes the first phase, that is the construction of the RL metamodel that formalizes the DSML's abstract syntax and is used to define its elements, relationships and modeling rules [5]. This metamodel is the result of a systematic review of the RL literature identifying the domain's core concepts along with its key attributes and relationships. The RL metamodel is the foundation of our approach for modeling and analyzing RL scenarios, using a domain-specific formalism [4]; and it aims to fulfill the needs of industries no matter their RL process. However, as products and legislation change among industries and countries, decision makers (e.g., government entities) will have the need to create specific models to analyze a given RL network. Hence, the need for a second phase where metamodel extensions are created, as illustrated in Sect. 5. This section first describes the mechanisms to extend the RL metamodel and then illustrates them in the context of current E-waste management regulations for Colombia.

The third phase entails the creation of further extensions to the metamodel that focus on the analysis methods that decision makers require to analyze their scenarios. For example, with the phase II metamodels it is impossible to apply techniques such as discrete event simulation, agent simulation, or SD because these metamodels focus mainly on static, structural aspects. However, by introducing additional concepts, attributes and relations targeted toward a specific analysis technique, it becomes possible to apply said technique on models created with the extended RL metamodel. This strategy of metamodel extension guided by the analysis technique has been applied in past works. For example, Manzur et al. [11] enriched ArchiMate [19] by adding elements to make possible the creation of architectural models for discrete event simulation.

## 4 The Reverse Logistics Metamodel

Next, we present the process to build a RL metamodel based on existing literature and expressive enough to address all of our concerns. To identify the core elements for the metamodel, we performed a systematic review of the RL literature. We limited the scope of our search to studies published in ranked peer-reviewed academic journals. A previous literature review by Agrawal et al. [1] on RL issues was found, which covers publications from 1986 to 2015. We updated this review by following the same selection and classification process for the missing period 2015 to 2018. Accordingly, six databases were considered: Elsevier, Emerald, Springer, Taylor and Francis, Wiley, and Informs. Given the main objective of our research, another exclusion criterion was defined: articles studying specific RL networks (e.g., closed-loop supply chains) or specific industrial applications were not considered. This resulted in a final set of 42 papers to complement those found in Agrawal et al.'s work [1].

As part of our analysis, we found that in the selected articles there is no agreement on the vocabulary to describe RL processes. To deal with this, we identified five clusters of terms used to describe closely related concepts: (i) Activity; (ii) Actor; (iii) Facility; (iv) Product; (v) and Regulator. Each cluster contains secondary clusters with finer grained terms also found in the literature review. Table 1 illustrates this by showing the Activity cluster which has 11 secondary clusters and the 66 terms.

**Table 1.** Cluster characterization for activities in RL

| Main cluster | Secondary cluster | Related terms |
|---|---|---|
| Activity | Storing | Storing (A), warehousing (A), inventory (A), inspection (H) |
| | Sell | Sell to secondary market (H), sales (A), marketed (A), resell (A) |
| | Disposal | Disposition (A), disposition cycle time (A), disposal (A), incineration (H), secure disposal (A), littering (H), land filling (A), destruction (H) |
| | Pollute | Pollute (A), leachate (H) |
| | Manufacture | Production, manufacturing, product assembly (H), parts fabrication (H), modules subassembly (H), re-manufacture (H), reprocessing (H), re-produce (H) |
| | Recycle | Asset recovery (H), material recovery (H), cannibalization of parts (H), reuse (H), informal recycle (H), upcycled (H) |
| | Recover | Recover (A), asset recovery (A), reutilization (H), refurbish (A), product recovery (A), repair (A), reconditioning (A), disassembly (H), product upgrade (A), renovation (A) |
| | Transportation | Reverse distribution (H), reverse transportation (H), distribution (A), delivering goods (A), redistributed (A) |
| | Collection | Retrieval (A), collecting used products (A), gate keeping (H) |
| | Purchase | Sale (A), consumption (H), purchase (A) |
| | Return | Return (A), return to supplier (H), commercial return (H), end of use return (H), EOL return (H), non-defective return (H), customer return (H), warranty return (H), service return (H) |

Following recommendations of the work by Babur et al. [2], which considers the definition and similarity of terms to discover clusters of elements, we established two types of relationships between terms in the literature: (i) analogous relations (A), when the terms are synonyms (e.g., manufacturing and production); (ii) and hyponym relations (H), which refers to subordinate connections in between concepts (e.g., manufacturing and product assembly). The complete literature review and the classification by clusters can be found on our website.

## 4.1 The Proposed Reverse Logistics Metamodel

The RL core metamodel defines and structures the key RL concepts identified after the literature review. Moreover, it allows the modeling of the network's controllable, static aspects, including a minimal subset of forward logistics concepts. Figure 2 depicts the core elements of each concept, the root of the metamodel (Return Flow) and their primary associations. It is possible that the attributes included in the metamodel may not be sufficient to model every specific RL scenario. Thus, this set of attributes is not set in stone and we have included the mechanisms to make it extensible: modelers might add more attributes and even new concepts in order to satisfy particular needs of analysis, as we explain in the following sections. The RL metamodel is organized around five clusters (see Fig. 2): (i) Activities, which refer to processes occurring in the RL scenarios; (ii) Actors, who guide and participate in those activities; (iii) Facilities, where the activities are performed or where production outputs are stored; (iv) Product related components, which represent the products themselves and their parts, their raw materials, their packaging, and the waste and pollution left after their usage and consumption; and (v) components related to Regulator entities that can create or terminate incentives for performing RL activities such as recycling.

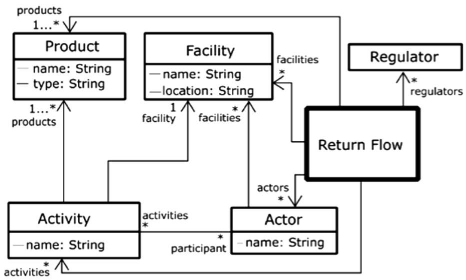


**Fig. 2.** The RL metamodel main concepts

Figure 3 shows the complete metamodel with the five key concepts and the root of the metamodel in bold lines, and with the elements that belong to each cluster as close as possible to them. Next, we present a brief overview of the metamodel, by following the typical sequence of a RL flow. The first activities serve to represent manufacturing or production, storage, transportation, and purchasing processes. Although these activities are widely regarded as belonging to the forward logistics domain, these activities are more likely to be controlled, thus enduring less uncertainty when starting from this point in the application of dynamic analysis to the RL models. To complement these activities, the metamodel includes related actors (e.g., manufacturer, and customer), facilities (e.g., factory, and warehouse), and sales channels which are all connected through associations. These elements were deliberately designed in a high-level manner to prevent the metamodel from becoming too large to be practical.

The second part of the metamodel refers to activities that pertain to the RL domain: disposal, pollute, recovery, recycling, collection, and returns. Disposal refers to activities that involve throwing away wastes in a facility such as a landfill. Likewise, to pollute refers to disposing pollutants into the natural environment (e.g., toxic wastes in a river). Recovery encompasses activities that return products to a state where they can be sold again for their original purpose (e.g., refurbishing, and reconditioning), as previously shown in Table 1. Similarly, recycling activities reduce products to their basic elements which can then be reused [15]. Recycling may refer to packaging, raw material, or any product part. Unfortunately, recycling and recovering can create their own waste and pollution. Collection is the selected term for activities such as gathering, filtering, and transporting previously sold products [15]. Return activities involve an actor who sends back a product to its manufacturer because the product either fails to meet his needs or fails to perform [15]. The final part of the metamodel includes regulators, which are in charge of the decision-making processes and influence RL chains by means of policies and controls. Regulators are not actors because they are not in direct contact with flows of products. However, they perform a critical role and have to be included in order to study how their actions influence the models' behavior.

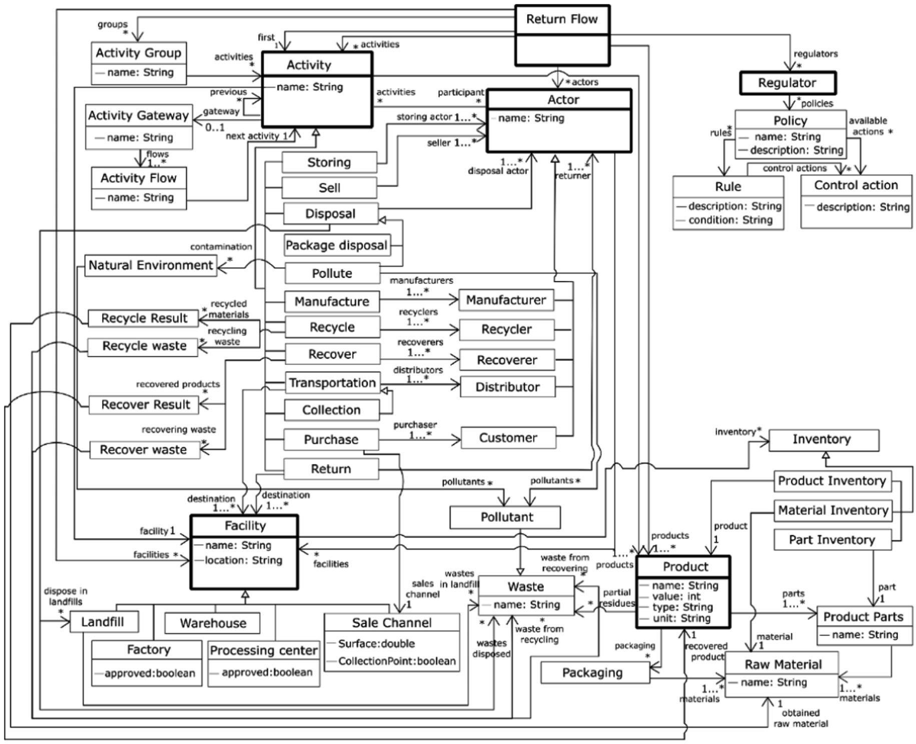


**Fig. 3.** The RL metamodel

## 5 Reverse Logistics in a Specific Context: E-Waste Case Study

While the RL metamodel groups the core concepts of any RL scenario, it is often necessary to have more specialized concepts to support the creation of more expressive models. In this section, we show how this can be achieved by extending and specializing the metamodel and illustrate this with a preparatory case study based on the E-waste management in Colombia. This case study is of interest because it targets a specific kind of waste with particular necessities regarding RL, and because the geographical localization provides a specific framework with respect to regulations. Over the last two decades, the amount of Electrical and Electronic Equipment (EEE) has continuously increased because of the rapid changes in information technologies, its increased accessibility, a downward trend in EEE prices, and a reduced lifetime for most products. As a result, a fast-growing number of EEE goods are reaching their EOL, generating vast amounts of E-waste [13]. An EEE is considered E-waste when it reaches its EOL and loses its original functionality, for instance, non-functioning or obsolete TVs, computers and mobile phones.

Given the importance of properly caring for E-waste streams, many countries have taken measures and have introduced policies to regulate its management. Based on a systematic review of the guiding legislations, we have identified one main principle and one derivative principle, described in Table 2 [14]. Today, most countries have EPR programs and policies in place. Nonetheless, their specific features and outcomes vary significantly across countries and industries. These variations cause a shift in the different RL processes and scenarios; this is where the need for extensions emerges, as the models shift from one country to another. For example, in South Korea the collection, treatment and costs are fully covered by producers through a collective scheme. To study how the metamodel adapts to the implementation of the EPR principle, we next analyze the case for E-waste management in Colombia.

**Table 2.** Principles for E-waste management

| Principle | Description |
|---|---|
| Extended Producer Responsibility (EPR) | Forces the producers or importers of EEE to be financially responsible for the entire life cycle of their products, especially when they become obsolete; and assumes that the producer will minimize the costs of E-waste management from the design phase of the product |
| Shared Responsibility (SR) | All actors (producer, retailer, government, final consumer) participate in the waste management and are responsible for its success |

### 5.1 Modeling E-Waste in Colombia

Colombia is one of the Latin American countries with the largest generation of E-waste. Estimations in 2010 shows that for a Colombian population of 46.3 million inhabitants, the E-waste generation is nearly 110.000 tons per year [12]. To deal with this situation the Colombian government has begun to regulate the EEE industry with the Law 1672 of 2013 and the Decree 284 of 2018, from the Ministry of Environment and Sustainable Development. This scheme follows the EPR principle and stimulates the adoption of RL practices since the producers are responsible for the recovery of E-waste. The Decree identifies all the actors involved in the E-waste management: producers, retailers, consumers, E-waste managers, environmental authorities, and territorial entities; and lists their obligations according to their role. In Colombia, customers can use the channels provided by both producers and retailers to deliver obsolete EEE devices to E-waste managers, who are responsible for either taking it back to producers (in its original form or as raw material), or to dispose them in a proper way. In this scenario, the government monitors and supervises parts of the RL network (actors, facilities, activities, inventories) and through incentives and penalties promotes a proper E-waste management aiming to reduce the use of informal alternatives.

To analyze the behavior of the presented case for E-waste management, it is necessary to extend the basic metamodel and adapt it to the specific context. Figure 4 presents the extensions added with newly added attributes and are shown in a grey shade. The elements added to the original metamodel arise from the study of the rules in the Colombian Decree that the core metamodel is not capable of supporting. The main extensions are: (i) definition of two additional attributes in the "Actor" entity allowing us to assess the responsibility of producers with the return of products: "Collection System" validates that the producers have an active collection scheme, and "Registry" validates that producers, distributors and E-waste managers are registered with the regulatory entities. Likewise, we added an attribute called "Fines" that sums up the value of all penalties imposed to an actor for breaking the law. (ii) definition of two attributes to "Sale Channel" that model the surface area of these points and the existence of collection points in them, as well as an attribute that guarantees that the "Processing Center" and "Factory" facilities are approved by relevant regulatory entities. (iii) addition of two "Action" specializations that specify the measures taken to enforce compliance with the law. These new actions are: "Penalty", applied to monitored actors for any breach of the law, or "Facility Closure", for lack of licenses and permits to operate. These extensions guarantee the expressiveness of the metamodel to describe the behavior of E-waste management in Colombia.

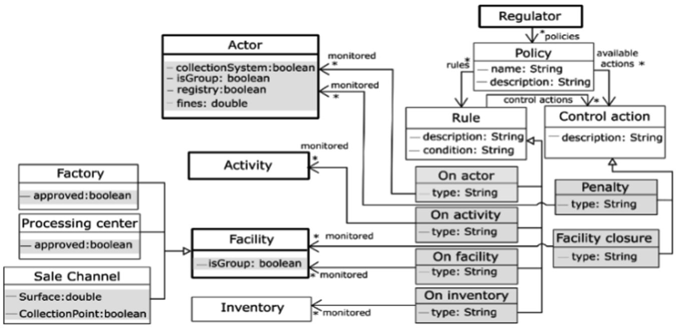


**Fig. 4.** Changes in the RL extended metamodel for the E-waste scenario in Colombia

## 6 Metamodel Extensions for Dynamic Analysis

In RL, it is often useful to explore "what-if" scenarios. These allow researchers, practitioners and decision makers to understand, analyze, and prepare for different outcomes regarding costs, quality and sustainability, whether they consider short- or long-term decisions. Thus, it is suitable to perform dynamic analyses, using techniques such as simulation, to comprehend the effects of the uncertainty in RL networks. However, for this to be possible, the metamodel must include elements, attributes, and relations representing dynamic aspects, and supporting specific analysis techniques, which can be achieved through an extension of a specific context metamodel for RL.

Using the same scenario, we exemplify the creation of an extension of the metamodel that can be used for dynamic analysis. The technique that is being applied to extend the metamodel is SD [16]. SD is a simulation technique to study nonlinear behaviors, centered around the concepts of flows and stocks: flows represent the movement of an element and stocks refer to the quantity of an element at a given time. In the metamodel, flows can be represented through RL activities and stocks can be stored in facilities. In order to support SD analysis of RL scenarios, the metamodel was first enriched with attributes to describe the outputs of activities (cost, value and quantity), and the stocks stored in facilities (initial and maximum capacities). It also requires a system to handle multiple units of measurement to perform unit conversions. Additionally, we can describe equations to specify changes in outputs or stocks of the model. The resulting metamodel is shown in Fig. 5 with the new extensions highlighted in grey. This metamodel extends the one proposed for E-waste management in Colombia in Fig. 4.

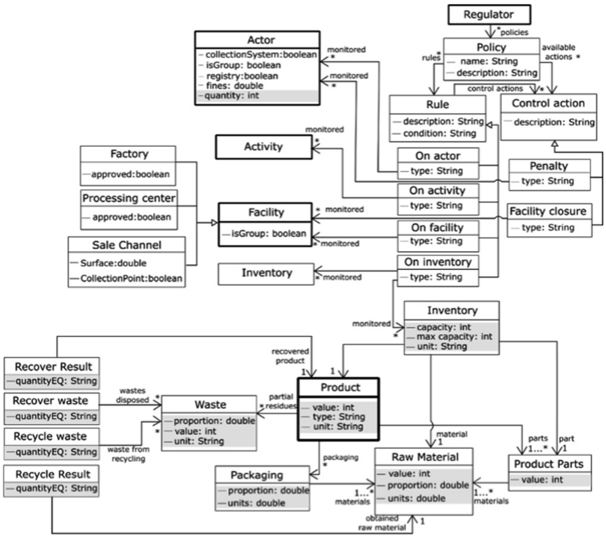


**Fig. 5.** Specific context metamodel extension: E-waste Colombian scenario for SD analysis

With this metamodel it is possible to establish a transformation schema from RL models to SD models that can be run with specific tools such as Stella's iThink. In this way, a modeler only has to construct RL models because their equivalent SD models can be automatically generated. The transformation schema, while not overly complicated, is more than an equivalence table: for each element in the RL model many elements may appear in the SD model. For example, for each kind of product and each facility where a product may be handled in the RL model, a stock has to be created in the SD model.

SD is not the only type of dynamic analyses that can be applied to the proposed metamodel. Any dynamic analyses can be used by including new elements and modifying current attributes and relationships with the dynamic components. For example, the E-waste metamodel for Colombia can also be adapted to support discrete event simulations (DES). These simulations differ from SD as they consider a discrete event in a given time, and each time an event occurs there is a change in the system's state. Thus, a model that supports DES has to consider components such as a system state, a time or clock, the events, and conditions in the system. DES has many suitable uses in the RL context, for example, process diagnosis, testing policies and prediction models.

## 7 Conclusions

RL management is a growing concern across industries and governments that requires problem-specific methodologies as well as generalized models even more so than in forward SC management. Research in the field has shown that the understanding, analysis and control of RL flows is highly complex mainly because of three issues. Firstly, RL processes face decisions in environments in which consumer behavior introduces unpredictability as a result of uncertainties in timing, quantities, and quality of an EOL product. Secondly, the lack of conceptual uniformity in between actors in the RL field hinders the development of the domain through combined efforts. Finally, the decisions and changes on a process are not short termed, they are generally reflected over a long term making their evaluation and improvement more problematic.

In this paper, we presented a model-based approach for creating RL scenarios considering the main issues of RL management and aiming to provide domain experts with tools they can use to study and analyze these flows. This paper has presented a proposal to create RL models through a core metamodel for analysis purposes and has focused on: (i) defining a generic metamodel, based on the RL state-of-the-art, that serves as a foundation for a DSML; (ii) extending the metamodel for particular domains; (iii) and extending the specialized metamodel to support specific analysis methods. This approach allows to address the lack of uniformity of the RL concepts through a standardization of the terms used along the RL process. The RL metamodel's concepts groups terms which describe the same or closely related concepts through the definition of clusters. Likewise, the metamodel allows domain experts to study and analyze using static and dynamic methods through the metamodel's extension mechanism. Particularly, this approach should be useful for regulators, which define RL policies and need to study "what-if" scenarios to improve RL capabilities, propose viable changes, or compare models' sustainability under different scenarios/policies. These extensions enable applying different analysis techniques to manage the RL flows in spite of the high uncertainty in the environment. For example, by giving information about the behavior of a network under an actual policy in the short, and long term, allowing to identify possible problems in the long term that are not visible at the beginning.

Based on the span of the literature review, the methodology used to identify the core concepts and the results with the preparatory case study on the E-waste Colombian scenario, we strongly believe that our proposal contributes to the main open issues in the field. Further research will provide domain experts with additional experimentation tools based on other simulation approaches (e.g., discrete events and agents).

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