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Assessing the Effect of Citizens' Behaviour in Textile Waste Separate Collection: An Agent-based Simulation Model

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Abstract

The purpose of this research is to analyse the impact of citizens' behaviours on the efficiency of textile waste separate collection systems within the framework of a circular economy. Using AnyLogic software, we model a municipal district where citizens might or not dispose of used clothes in designated roadside bins. The simulation explores two main aspects: the impact of citizens' behaviours and their mutual influence on system performance, as well as how service levels affect behaviour modification. Key findings reveal that citizen interactions significantly influence the system's efficiency, with higher bin and truck capacities leading to improved outcomes. However, a lack of environmental awareness among citizens adversely impacts the system. This study's novel contribution lies in demonstrating that mutual influence among citizens is a critical factor for an effective textile waste separate collection system. The value of this work is underscored by its alignment with EU Strategies for Sustainable and Circular Textiles, emphasizing the crucial importance of separate collection for achieving circularity in the textile industry. Policymakers and waste collectors should promote sustainable behaviours to optimize service performance and environmental benefits, ensuring compliance with upcoming EU regulations aimed at fostering a circular economy.

Keywords: Textile Waste Separate Collection; Agent-based Simulation; Citizens' Sustainable Behaviour; Circular Economy.

1. Introduction

The textile value chain is comprised of all the activities that include the sourcing of raw materials, product's design, manufacturing, distribution, retail, and eventual consumption. Additionally, it includes the end-of-life management of used and waste textile products (Moazzem et al., 2022). Each of these steps significantly contributes to environmental concerns. Indeed, throughout the textile processing stages—from fibre extraction to the utilisation of consumer-finished products—energy and various resources are consumed. The overproduction and overconsumption of textiles have led to significant waste and emissions. Additionally, the transportation and distribution of clothing and other categories of textiles demand substantial energy. These activities contribute to numerous environmental impacts, including greenhouse gas emissions, climate change, fossil energy use, land use, water use, human toxicity, and eco-toxicity on local, regional, and global scales

(Senthilkannan Muthu, 2020). In the EU, textile consumption ranks as the fourth highest contributor to environmental and climate change impacts, following food, housing, and mobility. It is also the third highest in terms of water and land use, and the fifth highest for primary raw materials use and greenhouse gas emissions (EU Strategy for Sustainable and Circular Textiles, 2022). These negative impacts stem from a linear supply chain model characterised by the overproduction of virgin fibres, low rates of usage, reuse, repair, separate collection, sorting, and fibre-to-fibre recycling of textiles. Moreover, this model often fails to prioritize quality, durability, and recyclability in product's design and manufacturing (Ellen MacArthur Foundation, 2017).

It is becoming increasingly important for the textile industry to redefine the concept of value, which is currently heavily reliant on the extraction of new resources to create new products. Decoupling value creation from resource extraction is indeed essential (Textile Exchange, 2023). Consequently, a key strategy to reverse this trend is the adoption of a circular economy framework, which offers substantial potential for reducing environmental impacts. This framework emphasizes the production of high-quality, durable products that are repaired and recirculated, maximizing their active use. At the end of their lifecycle, the materials are recycled into new raw materials suitable to be used in the same supply chain or in others. Transitioning from the current linear oriented textile supply chain to a circular one involves contributions from all stakeholders along the value chain. These contributions include changes in how textiles are designed, manufactured, sold, used, collected, and treated at the end of their lifecycle. Achieving circularity in the textile industry requires new circular business models, the development and promotion of separate collection, sorting and recycling technologies, political measures, and changes in consumer's behaviour (KÖHLER et al., 2021). Figure 1 illustrates how a circular supply chain differs from a linear one, as it aims to preserve the value of materials and resources in the form of functional products for as long as possible. In a linear model, the value chain starts with the extraction of raw materials (i.e. cotton or polyester) and ends when a user disposes of the product after use. Typically, products are discarded in an undifferentiated collection system, ultimately ending up in landfill or being used for energy recovery. The consumer then buys a new product, perpetuating the cycle of production and disposal. In contrast, a circular supply chain includes reverse loops, which reintegrate used products and materials into the economic cycle. In this system, the active lifetime of a product is extended through design for durability, repair, and sharing or passing on to other users when no longer needed by the original owner. At the end of the product's life, its materials become resources for creating new products through recycling (Ellen MacArthur Foundation, 2021).

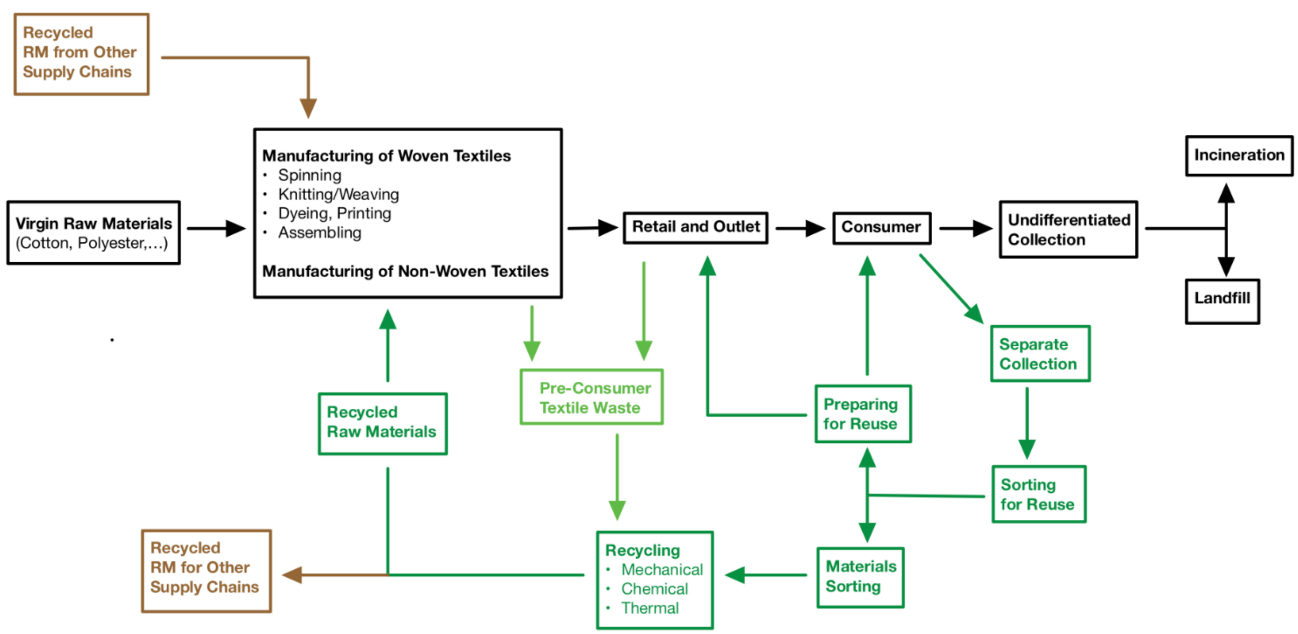

Figure 1. Graphical representation of a circular textile supply chain. Adapted from (Commission, Centre, Huygens, et al., 2023; Moazzem et al., 2022; Palacios-Mateo et al., 2021; Sandberg & Pal, 2024).

To address the current unsustainable conditions within the textile sector, the EU has developed the "Strategy for Sustainable and Circular Textiles". This strategy looks at the entire lifecycle of textile products and proposes coordinated actions and harmonised regulations for all the member states in order to change how textiles are produced, consumed and managed during end-of-life phases. The objective is to drive significant transformation, potentially creating a new industry that converts waste into value. According to the European Commission declaration (EU Strategy for Sustainable and Circular Textiles, 2022):

> By 2030 textile products placed on the EU market are long-lived and recyclable, to a great extent made of recycled fibres, free of hazardous substances and produced in respect of social rights and the environment. Consumers benefit longer from high quality affordable textiles, fast fashion is out of fashion, and economically profitable reuse and repair services are widely available. In a competitive, resilient and innovative textiles sector, producers take responsibility for their products along the value chain, including when they become waste. The circular textiles ecosystem is thriving, driven by sufficient capacities for innovative fibre-to-fibre recycling, while the incineration and landfilling of textiles is reduced to the minimum.

The shift from a linear textile supply chain to a circular one is closely tied to the implementation and expansion of textile waste management (McKinsey Apparel, 2022). Focusing on this topic, two classes of textile waste are normally defined (Wojnowska-Baryła et al., 2024):

- Pre-consumer waste: waste generated during the different stages of the textile's manufacturing (sometimes called post-industrial waste) and waste generated at retail stages (e.g. unsold textiles and returns);
- Post-consumer waste: textiles that have been disposed after consumption and use by citizens or end-users of commercial and industrial activities (hotel, healthcare, automotive, etc.), frequently called household and commercial post-consumer textile waste, respectively.

According to (Commission, Centre, Huygens, et al., 2023), the EU generates 12.6 Mt (Millions of tonnes) of textile waste per year (2019), of which 10.9 Mt are post-consumer waste and 1,7 Mt are pre-consumer waste. Currently, around 78% (8.5 Mt/yr) of the post-consumer textiles waste covering clothing and footwear, home textiles and technical textiles is not separately collected and ends up in mixed household waste, directed to be incinerated or landfilled. This resource-inefficient waste management is not in line with the waste hierarchy (Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on Waste and Repealing Certain Directives, 2024) and leads to environmental harm in the EU and in third countries through excessive levels of greenhouse gas emissions, water consumption, pollution and land use. Moreover, only 22% of the post-consumer textile waste generated in EU, corresponding to 2.44 Mt/year, is separate collected textile waste. To this amount should be added 0.33 Mt/yr of imported separate textile waste. As shown in Figure 2, of the total outcome:

- around 22% or 0.55-0.60 Mt/yr is recycled within the EU;
- around 7% or 0.188 Mt/yr, is reused within the EU;
- around 5% or 0.152 Mt/yr, is landfilled or incinerated within the EU;
- the rest is exported for reuse, landfill/energy recovery or recycling outside EU.

After separate collection, sorting for reuse defines a part of textile waste that is sent for preparing for reuse.

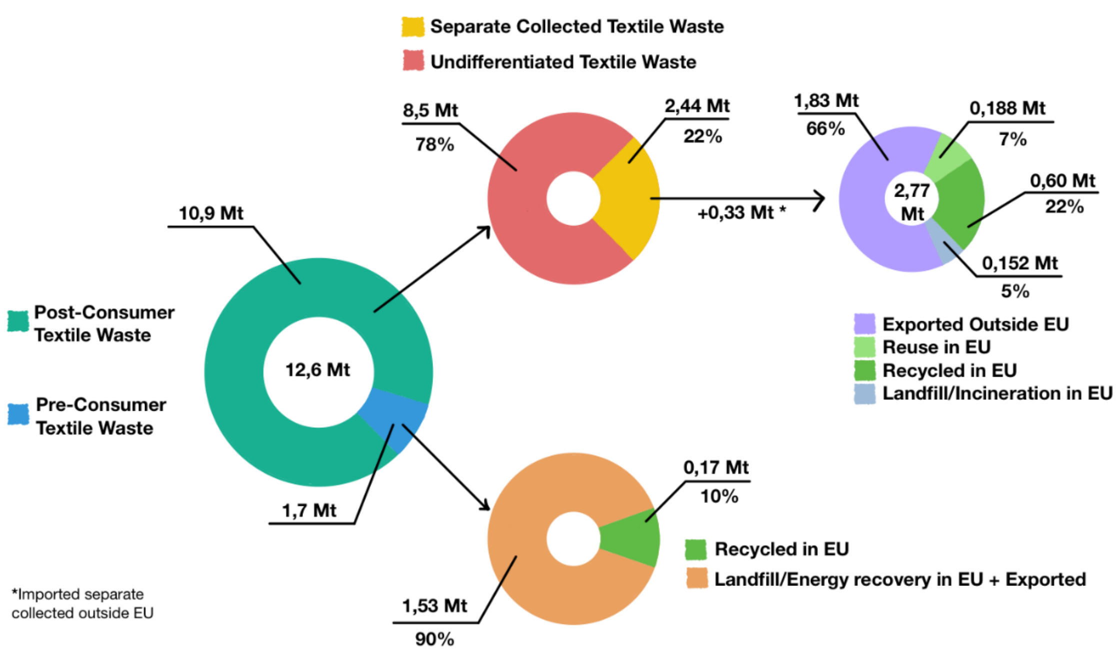

Figure 2. Textile waste mass flows in the EU. Based on data from (Commission, Centre, Huygens, et al., 2023).

The latter seems to be the best management option from an environmental and socio-economic perspective (Solis et al., 2024). The fraction that does not meet the quality requirements for preparing for reuse (Nørup et al., 2018) is mostly recycled, while low amounts of waste for energy recovery or disposal are generated after the sorting process. Most of this fraction, after materials identification (Zhou et al., 2019), is mechanically recycled for further use as cleaning rags or non-woven materials for the non-woven textile sector and other industrial applications (e.g. insulation material for construction or automotive sector) (Union, 2021). Together with the recycled share of pre-consumer waste (0.17 Mt/yr), the total mass that is effectively entering textile recycling plants in EU corresponds to 0.78 Mt/year. In the end, the amount that is currently recycled as spinnable fibres suitable to be used in the production of woven textiles is 0.03-0.05 Mt/yr, which corresponds to a share far lower than 1% of the total textile waste generated per year in EU.

We can appreciate from the presented data that the primary issues identified in textile waste management include the absence of separate collection and the export of unsorted fractions to countries where they may generate adverse environmental and social effects. Neither of these management approaches aligns with the waste management hierarchy, as they both involve incineration and landfill (Commission, Centre, Huygens, et al., 2023). An important solution adopted by the EU in order to address the absence of separate collection is the Waste Framework Directive (WFD), which states that all Member States shall set up separate collection for textiles by January 1, 2025 (Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on Waste and Repealing Certain Directives, 2024).

Given the importance and urgency of separate collection for enhancing circularity within the textile supply chain, it follows that the end consumer plays a crucial role in achieving this goal. To contribute effectively to close the loop through efficient textile waste management, end users need to perform additional tasks such as reducing the amount of waste generated, reusing, repairing, and adopting sustainable practices. This includes separating waste and delivering it to designated collection points on specific days. Without educational campaigns, community engagement initiatives, and incentives for pro-environment behaviours, they are unlikely to fully participate. Therefore, the collection system must be designed to support and enhance the propensity for participation by being as simple and efficient as possible, providing a high level of service. All subsequent waste management steps will benefit from such a design.

In light of these factors, understanding and modelling end-consumers' behaviour is crucial for the collection system design. Our work addresses consumers' behaviour in waste generation and disposal, adopting Agent-based simulation (ABS) because, unlike conventional Discrete Event simulation (DES), ABS allows for the mapping and reproduction of people behaviours and their mutual influences. This paper seeks to investigate the potential of agent-based simulation (ABS) for modelling citizen's behaviour within a circular textile supply chain. It specifically examines textile waste separate collection and the impact of service levels and human interactions on system design, optimization, and environmental sustainability.

The rest of the paper is organized as follows: Section 2 provides a literature review on textile waste separate collection, the adoption of simulation to evaluate and optimize the performance of household or municipal waste collection, and to predict waste generation based on the analysis of citizens' behaviour. Section 3 presents an ABS model of household textile waste separate collection, emphasizing the influence of citizens on one another and the impact of service level. Section 4 offers data analysis and discusses the implications of the simulated scenarios. Finally, Section 5 presents our conclusions and outlines potential future developments.

2. Literature Review

As discussed in Section 1, there is an urgent need for textile collection solutions. Municipal actors and waste companies in Europe are actively seeking efficient methods to meet the WFD's requirement by 2025. The first step in developing an effective textile waste management system is indeed separate collection, which segregates recyclable materials from residual or mixed waste, thereby maximizing the value of resources that would otherwise be incinerated or sent to landfill. This is particularly important for textiles because if they are thrown into undifferentiated waste, they can become moistened and degrade in quality, rendering them unsuitable for recycling (Commission, Centre, Albizzati, et al., 2023).

Main collection strategies for textiles typically consist of pick-up and drop-off schemes (Commission, Centre, Huygens, et al., 2023):

- Pick-up schemes: include door-to-door and kerbside collection.
- Drop-off schemes: involve underground and roadside containers placed in public areas where households or enterprises can bring their waste; collection centres; and take-back programs establish by retailers.

When focusing on household post-consumer textiles, various entities are involved in waste collection, including municipalities, charities, social enterprises, second-hand shops, and retail companies (Watson et al., 2020).

A crucial aspect in developing an efficient waste collection system is understanding consumer's behaviour and predicting the distribution of generated waste over time. Textile waste generation is characterised by high variability of volumes and heterogeneity of products and materials. This variability complicates the design of a system for the separate collection of textiles at the end of their lifecycle (Wojnowska-Baryła et al., 2024). Key parameters, such as the number and capacity of collection bins, the number and type of collection vehicles, the collection routes, and the location of bins or collection centres, depend on consumer's behaviour related to waste generation and sustainable disposal practices. Thus, consumers play a pivotal role in implementing circularity in the textile supply chain. Their demand drives overproduction and overconsumption phenomena, such as fast fashion. During the usage phase, consumers can influence the durability of their products and may also choose to repair them. Furthermore, they must be aware of the available options when a product reaches the end of its functional life. It is essential for consumers to discard products only when they cannot be given a second life through reuse (Nencková et al., 2020).

Currently, scientific studies have addressed consumer's behaviour regarding waste generation and disposal practices in various ways. For instance, (Puntarić et al., 2022) built a model to predict the amount of municipal solid waste using an artificial neural network. (Jäämaa & Kaipia, 2022) developed an explanatory model to predict the future flows of end-of-life textiles. (Nencková et al., 2020) presented a survey showing that demographic characteristics such as gender, age, education, income, and number of household members are statistically significant for understanding different attitudes towards textile waste separation.

As well, simulation has proven to be a valuable tool for addressing problems related to waste collection and consumer's behaviour. (Tong et al., 2023) combined the theory of planned behaviour and ABS to evaluate carbon emissions reduction through post-consumer waste recycling. (Cheng et al., 2022) built an interaction model incorporating two-way interactive information and perceived convenience to detect residents' waste separation behaviour and its rate of change using ABS and data collected from a survey. (Kummer et al., 2023) presented a solution using alternative infrastructures in cities for municipal solid waste collection by modelling a water-based system with hybrid simulation to optimize the operational processes on a recycling barge. (Meng et al., 2018) applied the ABS method to establish a model for the urban household solid waste separation and disposal system, aiming to predict behaviour changes of the main agents in the system under different policy scenarios. (Ribeiro-Rodrigues & Bortoleto, 2024) highlight that ABS is an effective tool for modelling pro-environmental behaviours, especially when these behaviours are difficult to measure and analyse empirically.

Thus, ABS proves to be a valuable approach for tackling issues related to the first steps of textile waste management, specifically in examining how citizens' behaviour influences the effectiveness of separate textile waste collection systems.

3. Materials and Methods

Our study utilizes an ABS model to replicate a system for the separate collection of textile waste. We employ the commercial software AnyLogic for this purpose (*AnyLogic: Simulation Modeling Software Tools & Solutions for Business*, n.d.). ABS is particularly well-suited to our objectives, as it is commonly used when modelers lack a comprehensive understanding of a system's overall features, but have insights into the behaviours of individual system's components. In ABS, a bottom-up approach is taken, focusing on the description of individual agents' behaviours and interactions. The global conduct of the system emerges from the multitude of concurrent individual actions (Law, 2015). This unique characteristic makes ABS ideal for examining how citizens' practices and interrelations impact the implementation of an efficient textile waste collection system, contributing to the circularity of the textile supply chain. Moreover, ABS allows for the evaluation of how the system's performance can influence citizen' attitudes in return.

The primary aim of our model is to analyse the impact of citizen behaviour on the design of an efficient and optimized system for collecting household post-consumer textile at the end of their lifecycle. Specifically, we investigate two crucial aspects:

1. How the mutual influence of citizens' behaviours, affect the overall performance of the system, in terms of environmental impact and provided service level.
2. How the impact of service level, might modify citizens' behaviour.

3.1. General Description of the Model

The model simulates an explanatory municipal district measuring 250 x 150 meters, inhabited by 999 citizens who periodically need to dispose of used clothes. There are four designated collection bins for used clothes within the district. These bins are emptied by a waste collection truck that operates on a fixed schedule, that is at the end of every week, starting and ending its route at a collection centre (located outside the district) where the collected clothes are stored. The truck moves at constant speed of 10 m/s.

Citizens with sustainable behaviour take their used clothes to the nearest bin and, if the bin is not full, deposit their items. If the bin is full, they dispose of the clothes in the undifferentiated collection bin at their home. Citizens who are not sustainably oriented always dispose of their used clothes in the mixed collection bin. In the model, each item of textile waste is represented as an integer number (e.g., 1, 2, 3, ...).

The operational dynamics of a waste separation system may involve citizens being discouraged from properly separating their waste when they encounter a full bin or find the area around the bin excessively dirty. Similarly, living in a neighbourhood where residents tend to disregard environmental sustainability can promote the spread of non-environmental behaviours. Therefore, our model considers several factors affecting individual consumers' willingness to engage in waste separation: (i) the level of service provided influences participation, with higher service levels leading to increased engagement; (ii) neighbours behaviour impacts individual actions, where virtuous behaviours encourage similar actions in others, and non-virtuous behaviours do the opposite.

To understand how the entire system evolves over time under various conditions, we developed a full factorial design of experiments (DOE) encompassing 72 different scenarios. These scenarios result from the combination of values for four input parameters (see Table 1). Each test spans one year, providing sufficient time to capture and represent the data variability. It is important to note that the system is designed so that the maximum truck capacity matches the total capacity of the bins (increasing it further would be unreasonable). Furthermore, when the *Radius of Influence* (*RoI*) is set to 0, only the effect of service level on consumer's behaviour is taken into account.

Table 1. Input parameters of the model.

Input Parameter	Possible Values	UoM
Bin Capacity	1000; 1250; 1500	unit
Truck Capacity	100%; 85%; 70% of Bin Capacity	unit
Radius of Influence	0; 1; 5; 10; 15; 20; 25; 30	metre

Table 2. List of metrics collected during simulation runtime.

Set of Metrics	Metric's Name	Scope	UoM
Environmental Friendliness	*SepWaste*	Amount of textile waste separate collected.	unit
Environmental Friendliness	*MixWaste*	Amount of undifferentiated textile waste.	unit
Environmental Friendliness	*DistanceTot*	Total distance travelled by the truck during its collection trips.	metre
Service Level	*% Poor SL*	Probability of finding a full bin.	%
Citizens' behavioural shifts	*Avg(p)*	Average value of *SustBehaviourProb* for a population after a year.	%
Citizens' behavioural shifts	*% IB*	Average improvement of citizens' behaviour.	%

At the conclusion of each simulation run, various sets of metrics were collected and analysed. These metrics are intended to provide insights into the service level of the collection system, the system's environmental friendliness, and the behavioural shifts of citizens over the course of one year (see Table 2).

3.2. Description of Citizens' Behaviour

Our model categorizes citizens into three distinct archetypes to replicate varying levels of environmental consciousness: (1) less environmentally aware, (2) moderately sustainable and (3) highly sustainable. These citizen types are differentiated by the initial values of the parameter *SustBehaviourProb*, set at 0.25, 0.50, and 0.75, respectively. This parameter represents the probability, that a citizen will properly separate textile waste upon disposal. Our differentiation may reveal varying attitudes toward textile waste separation within a municipal district, potentially influenced by demographic factors such as gender, age, education, and income. Each population contains 333 citizens, whose locations are defined randomly at simulation start up within the district. Moreover, each person moves at a speed of 1m/s if triggered. The behaviour of each citizen is defined using a state chart depicted in Figure 3.

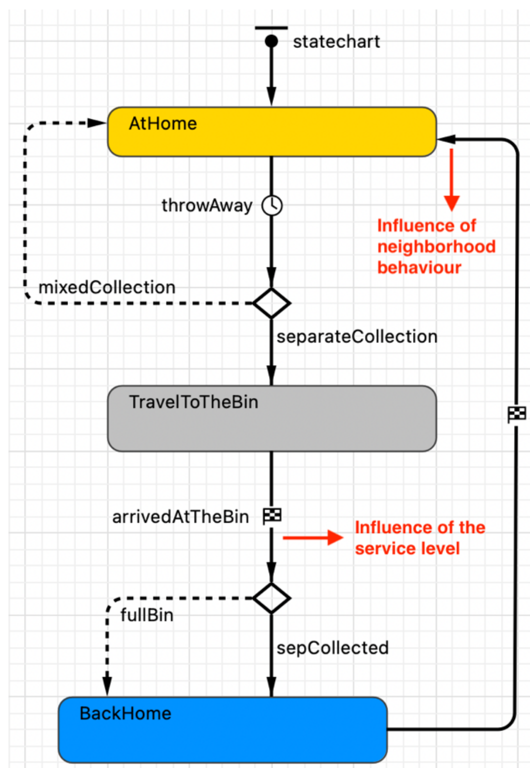

Figure 3. State chart of the citizen's conduct.

The state chart starts with the citizen being at home (i.e. *AtHome* state). The first state change is triggered by the *throwAway* timeout event that follows an exponential distribution with lambda parameter equal to 1 simulated week. At this time the person collects all the used clothes that he or she wants to dispose of. The generated amount of waste, say *GeneratedWaste*, is modelled as a triangular distribution with a minimum, modal and maximum value equal to 3, 8 and 30 garments, respectively. Also note that, as the first exclusive gateway of the state chart clearly shows, the citizen has two options:

- with probability p (equal to the parameter's value *SustBehaviourProb*) he or she has a sustainable behaviour and travels to the nearest collection bin;
- otherwise, with probability $(1 - p)$ he or she throws the used clothes in the mixed collection bin at home (simulating a non-sustainable behaviour).

In the second case the person immediately returns to the original *AtHome* state and the counter *MixWaste* value is incremented by *GeneratedWaste*. Instead, in the first case, he or she finds the bin closest to its home and moves to it (i.e. *TravelToTheBin* state). Then, as shown by the second exclusive gateway, when the citizen arrives at the bin two alternative scenarios are considered:

- If the sum of the bin's current quantity and the amount of waste brought by the citizen (*GeneratedWaste*) is less or equal than the capacity of the bin, he or she throws away the clothes and increases the current quantity of the bin. At the same time the counter variable *SepWaste* is incremented of the same amount. Additionally, if a citizen successfully disposes of their waste three time consecutively, his or her inclination towards environmentally friendly behaviour increases by 0.03, because of the development of more trust in the waste collection service provided.
- Alternatively, the citizen cannot throw away the clothes and he or she is forced to dispose of them in the mixed collection bin. In this case the amount of the counter variables *MixWaste* and *nFullBin* (which is a counter to keep track of how many times a citizen is unable to discard clothes due to a full bin) are incremented accordingly. Moreover, if the bin is full, the citizen loses confidence in the collection system, leading to a decrease in his or her inclination to act sustainably by 0.05.

At this point, in both cases, the state changes to *BackHome* (the person is returning home) and, finally, to *AtHome*.

Before returning to the *AtHome* state, each citizen's behaviour is adjusted based on the influence of their neighbours' actions. This adjustment simulates the word-of-mouth effect due to the day-to-day social interactions among people living in the same area or district. To simulate this effect, we assumed that the variation in each citizen's behaviour depends on the difference between the citizen's current value of *SustBehaviourProb* (p) and the average probability of having pro-environment behaviour of his or her neighbours (μ):

$$\Delta p = p - \mu \quad (1)$$

If the value of Δp is positive, the citizen tends to worsen his or her behaviour by an amount dp^-, otherwise if this difference is negative the citizen tends to increase his or her probability of separately dispose textile waste by an amount dp^+, where $dp^- > dp^+$. It must be noted that, because interactions between individuals are more likely among those who live close to each other, the mutual influence is assumed to decrease with distance. Therefore, the value of μ represents a (inverse of the) distance-weighted average, as indicated by equation:

$$\mu = \frac{\sum_{i=1}^{n} \frac{p_i}{d_i}}{\sum_{i=1}^{n} {d_i}^{-1}} \quad (2)$$

Where, the citizen i is one of the n individuals living in the neighbourhood (defined within a specific *RoI*) with *SustBehaviourProb* of p_i and distance of d_i, *i=1, 2, ..., n*.

Furthermore, the mutual influence effect is not deterministic, but there will be a certain probability of its occurrence. The likelihood of behaviour modification is calculated using an exponential decay, similar to that of Simulated Annealing (Ball et al., 2024), as shown in equation:

$$\pi = \alpha \cdot e^{-\beta \cdot (1 - |\Delta p|)} \quad (3)$$

Where, α indicates the value of π when the gap Δp is at its maximum (equal to 1), while β determines how quickly the exponential growth occurs. We assumed α equal to 0.9 and β equal to 2.5. Consequently, the probability of a modification occurring decreases exponentially as Δp approaches 0. Thus, two scenarios may occur:

- If Δp is less than or equal to 0 and a random true event occurs with probability π, then there is an increase in *SustBehaviourProb* by dp^+ (set at 0.03).
- Otherwise, if Δp is greater than or equal to 0 and a random true event occurs with probability π, then there is a decrease in *SustBehaviourProb* by dp^- (set at 0.05).

Finally, the citizen enters the state *AtHome* completing its cyclic behaviour. The process is reiterated until the simulation ends.

4. Results and Discussion

The results of the 72 simulation scenarios, each representing a unique combination of the three input parameters, are presented and discussed in this section. As mentioned in Table 2, six metrics has been collected at the end of each simulation run, namely: (i) *SepWaste*, the amount of separate collected textile waste; (ii) *MixWaste*, the quantity of textile waste that ends up in the undifferentiated waste collection; (iii) *DistanceTot*, the total distance travelled by the collection truck; (iv) *% Poor SL*, probability of finding a full bin; (v) *Avg(p)*, the average value of *SustBehaviourProb* in each population at the end of one simulated year; (vi) *% IB*, which measures the percentage change in the average value of *SustBehaviourProb* in each population from the start to the end of the simulation run.

The results were compiled into a table, which was not included in the paper due to space constraints. Following this, a data analysis was conducted. This analysis revealed a very high variability across the scenarios and, more importantly, significant declines in the willingness to participate in textile waste collection due to the interrelations between citizens. Additionally, the value of *SepWaste* never exceeded that of *MixWaste*. Higher bin and truck capacities led to better results across all metrics. However, if a significant portion of citizens lack environmental awareness, it detrimentally impacts the performance of the entire collection system.

In the following subsections, we aim to analyse the most relevant highlights of the collected data, considering the impact of individual parameters.

4.1. Impact of Bin and Truck Capacities

Holding the *RoI* constant, we observed that higher bin capacities result in a greater amount of waste being separately collected and a better service level. In contrast, the truck capacity does not significantly affect the amount of waste correctly collected but greatly influences the total distance travelled by the truck, thereby impacting environmental factors such as GHG emissions.

Bin Capacity and *Truck Capacity*, which are key parameters for dimensioning the collection system, also influence the behavioural shift of citizens. From this perspective, truck capacity has a negligible impact because it is highly unlikely that a citizen will encounter a full bin during the time interval of the collection trip. However, as previously mentioned, this parameter is crucial for sizing the system because a lower truck capacity results in more trips, leading to higher resource consumption and increased emissions. On the contrary, higher bin capacities contribute to increase *% IB* across all three populations (population 1 = less environmentally aware, population 2 = moderately sustainable, and population 3 = highly sustainable). This outcome is more pronounced for higher values of *RoI* and is most evident when there is no reciprocal influence between citizens. In this specific scenario, when the bin is set to maximum capacity, behavioural improvement in all three populations is evident with values of approximately 5%, 8.5%, and 10%, respectively. Conversely, when bin capacity is set to its minimum, there is a decrease in citizens' behaviours by approximately 29%, 24%, and 25% compared to the initial situation. A sample standard deviation of approximately 15% characterizes the values of % IB1, % IB2, and % IB3 across the nine scenarios where reciprocal influence between citizens is not considered, and only the impact of service level on behavioural shifts is taken into account. This deviation is the highest when altering the *RoI* value, highlighting how the sizing of the collection system can have a relevant impact on citizens' behaviour.

Thus, regarding the parameters *Bin Capacity* and *Truck Capacity*, we can conclude that for improved environmental friendliness and efficiency of the collection system, bins must be larger to accommodate all potential discarded clothing. This would also positively influence citizens' behaviour, as they would develop greater trust in the system. Additionally, the truck capacity must be set to 100% of the total bins capacity in order to complete the collection route without needing to return to the collection centre to unload. This would reduce the environmental impact by minimizing the distance travelled.

4.2. Impact of the Radius of Influence

Now, focusing on the impact of the *RoI*, our results show that increasing this parameter positively affects the amount of separately collected textile waste and the *% IB* across all three populations. However, under our defined assumptions, populations 2 and 3 consistently exhibit a decrease in the average value of *SustBehaviourProb* compared to their initial attitudes (50% and 75%, respectively) when the *RoI* is varied from 1 to 30 meters. It is important to note that increasing this value beyond 30 meters is ineffective, as no substantial changes in results are observed due to the model's dimensions. Only at a *RoI* of 25 and 30 meters does population 1 show an improvement in behaviour compared to its initial value of 25%, but this is contingent on the bin capacity being set to 1500.

Table 3. Results of the eight scenarios with parameters *Bin Capacity*=1500 and *Truck Capacity*=100%.

RoI	*SepWaste*	*% Poor SL*	*Avg(p) [1]*	*Avg(p) [2]*	*Avg(p) [3]*
1	138328	0,70%	3,40%	6,40%	9,70%
5	162094	0,97%	7,00%	10,30%	15,30%
10	207838	1,37%	16,20%	18,50%	24,00%
15	228314	1,34%	21,00%	23,90%	25,30%
20	239704	1,33%	24,70%	25,30%	26,90%
25	235204	1,42%	25,10%	25,90%	25,40%
30	239953	1,32%	25,60%	26,10%	26,10%
0	311367	11,82%	26,20%	54,20%	82,20%

Table 3 presents the results of the eight scenarios, in which maximum values of parameters bin and truck capacity are fixed. Here, the purpose is to illustrate how varying the *RoI* affects the amount of waste separately collected, the service level, and the average value of

SustBehaviourProb (*p*) across the three populations at the end of the simulation (*Avg(p)*).

An interesting aspect emerges when comparing scenarios where there is reciprocal influence on behaviour between citizens versus the scenario where citizen behaviour is influenced solely by the service level of the collection system (*RoI*=0). When citizens' behaviour is influenced by their neighbourhood, we generally observe a deterioration in the average behaviour of all three populations compared to the initial situation. Conversely, when only the service level impacts behaviours, there is a significant improvement in the populations' propensity to act sustainably in disposing used clothes. In this latter case, we also find the highest percentage of separately collected textile waste relative to the total waste generated, reaching 45.52%. Additionally, we can see from Table 3 that in this scenario, the *% Poor SL* stands at 11.82%, indicating that the collection system failed to collect a significant amount of potential textile waste. Addressing this issue could have led to even better results. It must be noted that low values of % Poor SL are not always beneficial, as they can result from a decrease in sustainable behaviours across the population. This means more people are discarding their used clothes in the undifferentiated bin at home, hindering the system for separate collection. Conversely, the scenarios in which mutual influence among people is present, generally show substantially lower performances in terms of *SepWaste* quantity and changes in citizens' behaviour compared to the scenario with a *RoI* equal to zero. However, as the mutual influence among people intensifies, we notice a gradual improvement within the observed metrics.

To delve deeper into the analysis of shifts in consumers' behaviours with varying *RoI*, Figures 4, Figure 5, and Figure 6 illustrate the monthly trends of the average *SustBehaviourProb* value across the three populations for scenarios with RoI set at 5, 30, and 0, respectively. For these scenarios, both bin and truck capacities are at their maximum levels. Additionally, the overall average trend across the three populations is depicted in purple (*Gen Avg(p)*).

By comparing Figure 4 and Figure 5, we observed that a *RoI* of 5 metre results in a decreased average probability of pro-environment behaviour across all the three populations. Conversely, by increasing the *RoI*, particularly to a value of 30, populations 2 and 3 tend to elevate the average propensity of the least sustainable population, but this increase only persists until a certain point. Specifically, after peaking at 36.80% in month 4, the trend starts to decline, and by the end of the simulation (one year), the general average stands at 25.93%. This finding is crucial, as it indicates that mutual influence among citizens, which represents varying intensities of community and social interrelations, can significantly impact system performance. Moreover, the amount of separately collected textiles is substantially higher in scenarios with a higher *RoI*.

Furthermore, the data presented in Figure 6 reinforce the aforementioned finding. Specifically, if the service level is the sole factor influencing citizens' behaviours (*RoI*=0), the average value of *SustBehaviourProb* shows an increase compared to its initial value across all three populations. In this scenario, a markedly more environmentally friendly and efficient system emerges over a one-year period. This is evidenced by the increased amount of separately collected textiles and the overall improvement in citizens' behaviour across all population types.

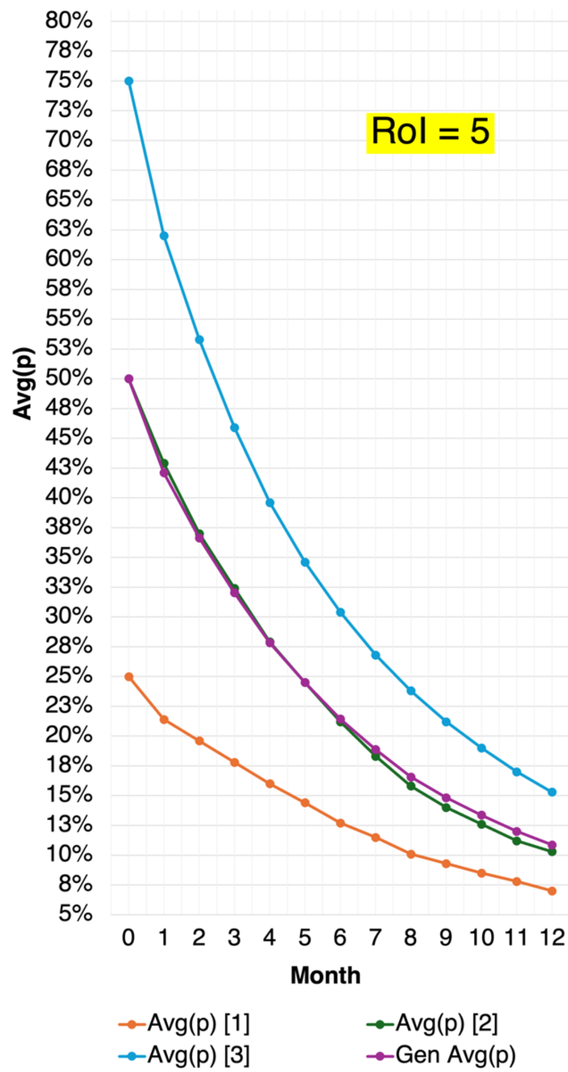

Figure 4. Monthly trends of the average *SustBehaviourProb* (*p*) value across the three populations, with *RoI*=5.

In conclusion, mutual influence among individuals emerges as a critical factor in developing an effective textile collection system. Its significant potential to positively or negatively impact the system depends on whether the community's environmental attitudes and practices are eco-friendly. Considering the service level alone is insufficient for designing a high-performance textile waste collection system. While service level is crucial in modifying consumer's behaviour upon disposal, the latter is also profoundly influenced by interpersonal relations within the community. Therefore, municipalities and waste collectors, with the support of policymakers, should develop incentives and communication campaigns to promote sustainable behaviours among all citizens. This approach would generate an exponential positive effect on the amount of textile waste collected, reduce variability in waste generation over time, and thus enable collectors to optimize their services from both economic and environmental perspectives.

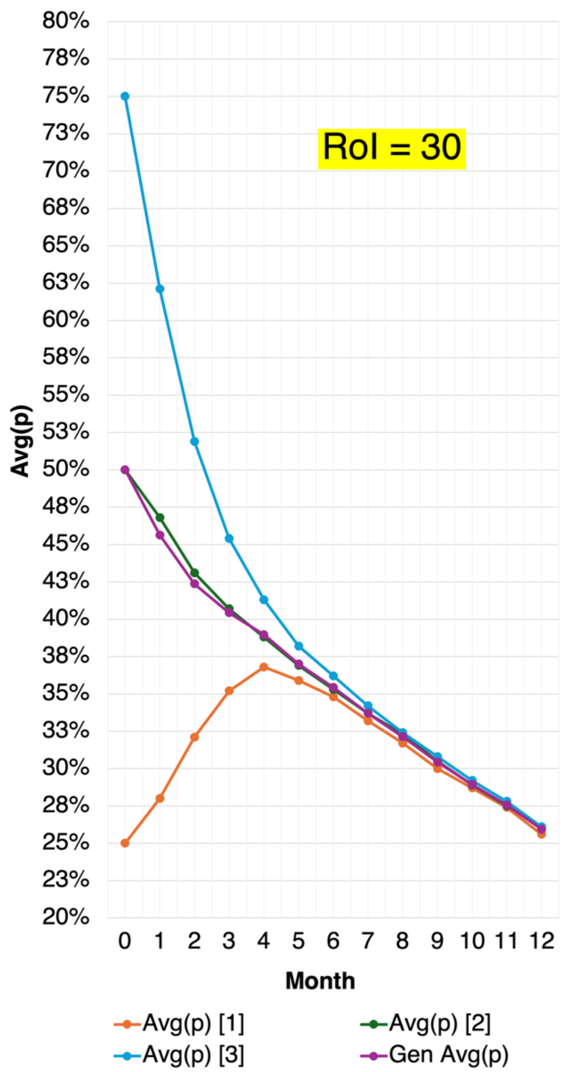

Figure 5. Monthly trends of the average *SustBehaviourProb* (*p*) value across the three populations, with *RoI*=30.

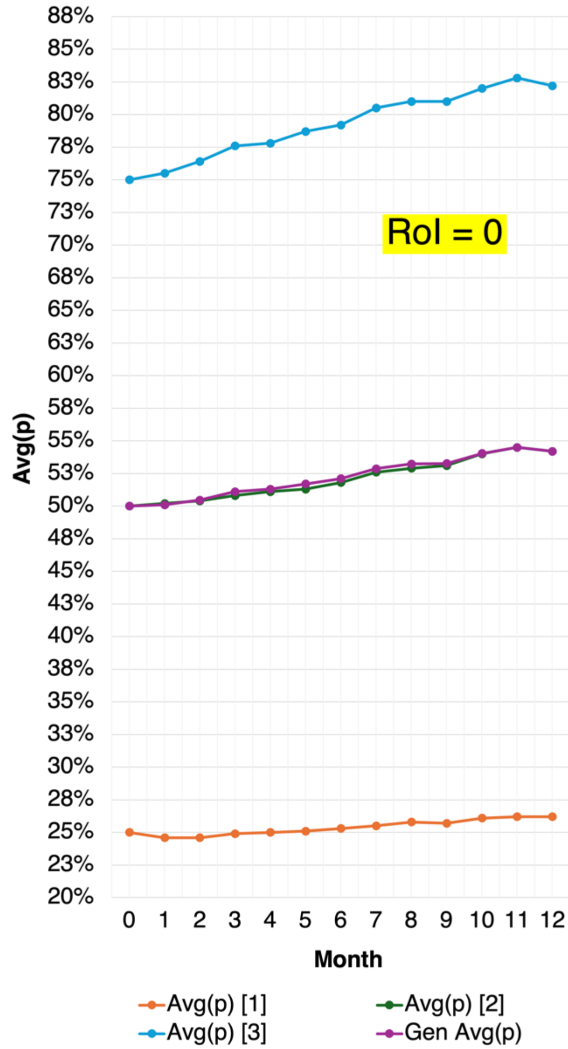

Figure 6. Monthly trends of the average *SustBehaviourProb* (*p*) value across the three populations, with *RoI*=0.

5. Conclusions and Future Developments

Our paper examined the current challenges of the textile supply chain and demonstrated how implementing a circular economy framework can enhance the sector's environmental sustainability. A key aspect contributing to this goal is the development and scaling up of a textile waste management system, where textile products at the end of their lifecycle are separately collected, sorted, reused and recycled into raw materials for the textile supply chain or other supply chains. This approach diverts waste from incineration and landfill, which entail detrimental environmental impacts. Implementing separate collection for textile waste is a crucial step in this transition, yet it is currently lacking. To address this issue, the EU introduced the Waste Framework Directive (WFD), which mandates that all Member States establish separate collection for textile waste by January 1, 2025. In this context, our work focuses on consumer's behaviour in textile waste generation and disposal. We developed an ABS to accurately replicate the behaviours of citizens within a municipal district. The model demonstrates how mutual influence among citizens and the impact of service level on citizens' behaviour affect the design and operations of a waste collection system in terms of environmental friendliness and effectiveness of the service. The results of our model show that mutual influence among people plays a crucial role in developing an effective textile waste collection system. This social dynamic significantly impacts the system's overall performance, highlighting the importance of community behaviour in environmental initiatives. When the prevailing environmental attitudes within the community are eco-friendly, there is a synergistic effect among citizens. This leads to higher rates of textile separation, increased participation in recycling programs, and a more substantial collective effort towards sustainability. Conversely, if the community's environmental practices are not eco-friendly, mutual influence can have a detrimental effect. Negative behaviours can spread, leading to lower rates of textile separation, reduced engagement in recycling programs, and an overall decline in the system's efficiency. This underscores the necessity of fostering positive environmental habits within communities to leverage mutual influence effectively. Moreover, the impact of mutual influence can shape long-term behavioural norms and cultural practices around sustainability. By promoting and reinforcing positive environmental behaviours, municipalities can create a self-sustaining cycle of improvement, where eco-friendly practices become the norm. This, in turn, enhances the resilience and adaptability of the textile waste separate collection system, reducing its intrinsic variability. Therefore, stakeholders in textile reuse, sorting, and recycling stand to benefit from the increased and more consistent volume of collected waste. This advancement can significantly scale up the circular economy in textile industry, thereby diverting value creation from resource extraction. Additionally, policymakers, municipalities and entities involved in the textile waste management sector (such as non-for-profit organisations), must consider the role of mutual influence in their strategies. Efforts to improve textile collection should include educational campaigns, community engagement initiatives, and incentives for positive behaviour. By harnessing the power of mutual influence, it is possible to create a more robust, efficient, and sustainable textile collection system that benefits both the environment and the community.

Nevertheless, we recognize the limitations within our work. Each textile product remains a discrete entity in the model and it lacks in replication of real-world environments with GIS (Geographic Information System) coordinates. Additionally, the model does not include an impact analysis concerning economic and environmental factors (i.e., Life Cycle Analysis), and the input data are far from being realistic. To fully harness the potential of this approach, which stems from simulation, we will work on further implementations with the collaboration of companies in the waste management sector. Future developments will include: (i) Integrating the system into an actual GIS environment within a real municipal district; (ii) Distribute surveys to assess consumers' behaviours and preferences; (iii) Incorporating vehicle routing and bin location problems to optimize routes and bin placements; (iv) Conducting a proper DOE analysis, including variance analysis, to understand the significance of effects and combined effects; (v) Evaluating the distribution of citizens in non-random patterns by defining neighbourhoods with different percentages of the three classes of citizens; (vi) Testing the environmental and economic performance of various methods for separately collecting textile waste, such as pick-up and drop-off schemes; (vii) Introducing economic incentives to improve participation and efficiency.

These improvements will contribute to develop a more realistic and effective model for textile waste management, providing a valuable tool for decision-making by municipalities, waste management companies, and policymakers.

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