Modelling Key Performance Indicators in a Gamified Waste Management Tool

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Abstract: Broader understanding of waste management has the potential to bring about broad societal change impacting the climate crisis and public health. We present existing waste management tools and commercially-available games involving waste management, highlighting the strengths and opportunities left unaddressed by these tools in educational contexts and planning use cases. A survey motivates the need for enhanced interactive tools providing clear feedback through quick-visibility performance indicators. After identifying an opportunity to build upon highly-detailed multi-criteria simulation tools, we explore the need for easy-to-read performance metrics that will bring to the field of waste management easily identifiable and measurable key performance indicators (KPIs) that vary alongside factors affecting waste management policies. Such metrics are introduced and detailed as part of a unified waste management model. We then develop a representative gamified educational tool based upon this model to be used by students, decision makers planning real-world policies, and the public. This simulator is built upon the Unity Game Engine and emulates waste management techniques and resulting KPIs within the context of a virtual city.

1. Introduction

Waste management is an increasingly visible and essential element to functioning civilization. It is a particularly critical area of study in addressing growing climate [1] and public health [2] crises, yet in-depth exploration of this important topic is often not feasible to the average person as knowledge barriers and challenges relating to data access hinder public education efforts. In truth, it is these "average" individuals who most contribute to these problems and—through behavioral changes—might best support their amelioration.

Increasing public awareness of challenges and opportunities in waste management has the potential to bring about significant positive change. However, while the theory of waste management is studied widely, and observational data from real-world cities contribute to our modelling of it, waste management remains for many a difficult concept to understand–particularly as far as drivers of change are concerned. For many, a lack of "hands on" data makes developing intuition difficult. For others, poor understanding of critical evaluative performance metrics makes it tough to understand what effect policies might have on waste generation and management.

Though tools have been developed to quantify waste management efficacy, and simulators have been built to allow individuals to "pull the levers" in a virtual environment to gauge their impact, these metrics and simulators are needlessly complex and therefore only serve a small audience. Existing simulations map inputs to performance indicators, requiring a complex setup to develop and adapt models for environments such as cities. This expertise requirement poses a barrier to knowledge that limits individuals' understanding of waste management systems, whereas broader knowledge of waste management could contribute positively towards the creation of enhanced social policies and constituent engagement in an effort to reduce and manage waste.

There is an opportunity to create an informative, easy-to-use simulator to help all types of individuals build an understanding of waste management and to evaluate the impact of various changes on waste management performance, particularly in the context of gamified tools. Building an understanding of challenges and opportunities within a larger network has the potential to drive positive change in waste generation and management. To that end, we build an educationally-focused tool in which students engage with a virtual city, changing operational parameters and observing these parameters' impact on waste management performance. Adding to the novelty of the designed simulation is an automated approach to selecting critical parameters and indicators to share with end users, helping to select the most-informative features as a means of educating users on what to look like when characterizing or designing their own waste management systems.

In this paper, we present existing waste management tools and commercially-available games involving waste management, and highlight the strengths and opportunities left unaddressed by these tools in educational and planning use cases. A brief survey motivates the need for enhanced interactive tools focused on providing feedback through quick-visibility performance indicators. After identifying an opportunity in building detailed tools with enhanced multi-criteria simulation capabilities, we explore the need for easy-to-read performance metrics that will bring to the field of waste management easily identifiable and measurable key performance indicators (KPIs) that vary alongside factors affecting waste management policies. To address this need, we develop a representative gamified educational tool to be used by students and decision makers planning real-world policies. This custom-built simulator is built upon the Unity Game Engine and emulates waste management techniques and resulting KPIs within the context of a virtual city.

2. Prior Art

This section presents commercial games and research tools that include as a central theme elements of waste management and waste management modelling. We present popular games such as "Sim City 4" and "Cities: Skylines" alongside research tools like "NetLogo" and explore the level of depth of their waste management approach as well as their relative strengths and opportunities for improvement.

2.1. Simulation Games and Gamified Tools

Within cities, large populations and small regional boundaries lead to significant accumulation of solid waste, making waste management—whether through reduction, reuse, or recycling—essential. While waste is typically undesirable, elements of its management can be made "fun" through the exploration of waste management techniques in games such as those related to city building. One such example is the SimCity franchise of games, which was first released in 1989 and has since witnessed four significant updates. Each version includes increasingly-advanced waste management features. Haupt, Arnold, and Bidlingmaier found that *SimCity 3000* (1999) and *SimCity 4* (2003) included infrastructure systems that were comparable to real-world cities and realistic enough to support research [3,4]. *SimCity 4*'s updated waste management system (elements of which are visible in Figure 1) is notable as the definitive version for research [4]. In this model, all waste created in the city fall are grouped together as "garbage", though there are three different ways to dispose of the city's waste: landfill, recycling, and energy conversion, with each having positive

and negative associated attributes. Landfill is inexpensive when disposing of waste in small amounts, but it becomes expensive to maintain as the landfill reaches capacity—and residents find proximity to the dump undesirable. Recycling reduces the percentage of garbage relative to waste within the city, but may be cost-prohibitive. The waste-to-energy plant creates power for the city while eliminating significant waste, but it creates pollution and generates small amounts of power. *SimCity 4* informs users of how well they manage the city's waste through different reporting means, including the city's desirability score and the user's Mayor Rating (https://simcity.fandom.com/wiki/Mayor_rating, accessed on 24 October 2021), which both depend partially on how much garbage has piled up within the city. This rating varies from −100 to 100 and indicates citizens' approval of the mayor based on policies enacted, decisions made, and city statistics. The metric provides a quick "gut check" for players to determine sentiment related to their policies comprising social, economic, and other factors in one key performance indicator.

Figure 1. Landfill and waste-to-energy plant are potential options for waste management in *SimCity 4*.

Other city-building games have been used for urban development and waste management research –Fernández and Ceacero-Moreno [5] tested *Cities: Skylines* (2015) to see if it met the standards necessary to train environmentalists with gamified training scenarios as well as to see if it was able to correctly identify and manage natural hazards that occurred in the city. *Cities: Skylines* was also tested and scored in waste management, as well as energy production, and health systems, and it was deemed sufficiently realistic to be used in gamified learning [5]. *Cities: Skylines* is like *SimCity 4* in that it groups all types of waste as garbage, and all garbage can be treated or disposed of through various means. In *Cities: Skylines* (Figure 2), waste disposal options include a floating garbage collector for contaminated water, an incineration plant, a landfill site, a recycling center, an ultimate recycling plant, a waste disposal unit, a waste processing complex, and a waste transfer facility. These methods all have trade-offs, such as the waste disposal unit creating a small amount of energy in exchange for a lot of pollution. One notable way in which *Cities: Skylines* varies from *SimCity* is that some methods, such as the waste processing complex and the recycling center, produce recycled materials from the waste, providing

users with incentive to buy into more expensive recycling methods. Every building in the city also has a garbage buildup meter showing how much garbage the building has and its remaining capacity. If a building fills up with garbage, users are informed of the need to empty the building lest it be abandoned. Research into both the *SimCity* franchise and *Cities: Skylines* shows that commercial games are realistic enough to be viable for use in gamified research and education, which makes their systems valuable to urban planning and waste management.
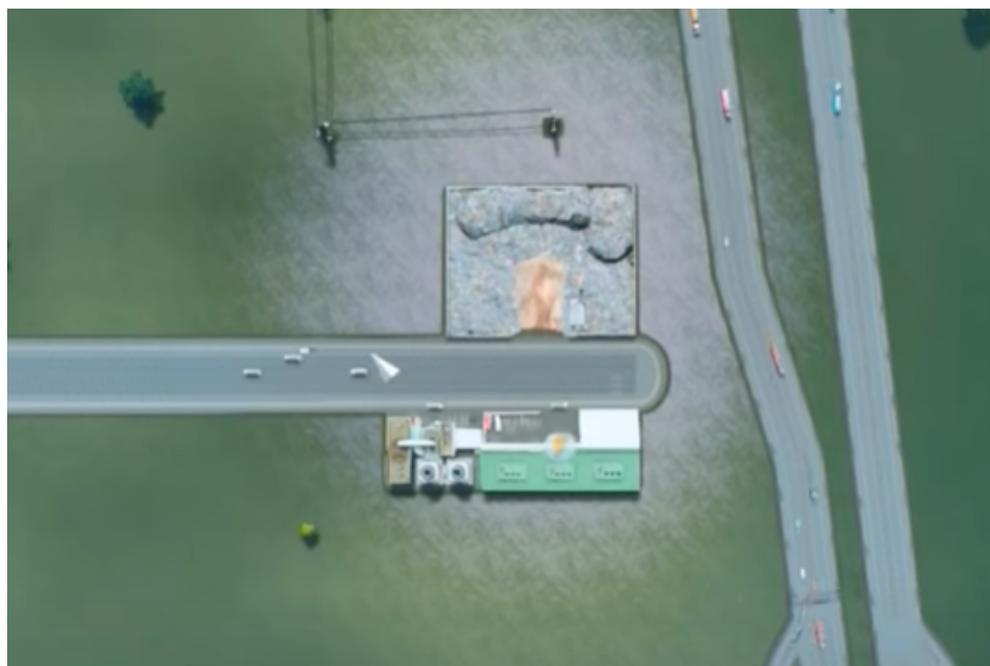
Figure 2. The Recycling Center, Incineration Plant, and Landfill Site are among the waste management options available to players of *Cities: Skylines*.

There have been recent research efforts to study the use of serious games in teaching and evaluating strategies for urban waste management. Wu and Huang created a waste management simulation game (Figure 3) that allows participants to control a city including its waste management, and see the ramifications of their decisions on the city [6]. Simulation users see waste accumulating in their city through a representative number of trashed 3D soda cans that litter the city's streets if waste is not adequately managed. The effects of this waste are also communicated to users through "official reports", which provide users with feedback and results related to their waste management choices, for example with one report informing users that the dogs in the city are getting sick as a result of consuming trash. Wu and Huang tested their waste management simulation on two subject groups, Taiwanese undergraduate students and Taiwanese elementary school students, and tracked both groups' decisions relating to balancing economic growth and the ecological effects of increased pollutants. Their research found that the undergraduate students generally put more importance on economic growth while ignoring the negative effects on the environment, while the group of elementary school students tried to balance economic growth with limiting environmental pollution, leading to issues with untenable resource allocation in other areas. Both situations focus on a core concept in teaching waste management, notably that there must be compromise. A city may hire more waste management workers and build more garbage trucks, but that will come at a monetary and environmental cost—not to mention the need to sequester or otherwise dispose of the waste.

Figure 3. Wu and Huang's Waste Management Simulation Game evaluated two groups' planning decisions with respect to economic and environmental impact (Adapted with permission from Ref. [6]).

Wood of War is a serious game for waste management research created by Salazar et al. [7]. This game (Figure 4) uses mobile user data to identify areas with excessive solid waste build-up in Colima, Mexico throughout gameplay, and then compares these data to a map of areas in Colima, Mexico with significant amounts of rainfall to identify potential risk points where rain and trash could mix, blocking sewer drains and causing flooding. The game encourages players to go to these areas to destroy or dispose of enemies modeled to resemble sentient trash into piles of waste. Users are given extra points if they find a new area of excess waste and tag it using GPS for the developers [7]. This cycle of finding enemies in the real-world waste and finding trash-laden locations for more points-bearing enemies keeps game participation high and allows the developers to collect data valuable to local waste removal services [7]. Serious games like *Wood of War* can be specialized to a specific area of need like Colima, Mexico, where urbanization has been steadily growing in recent years while the waste management system is struggling to keep up with its urban population's excess waste. The game identifies areas of importance for waste management officials to address such that associated negative externalities, such as flooding from blocked sewer drains, can be managed responsively. Understanding where waste build-up occurs most frequently by using the game's data can also help officials build more efficient waste removal routes.
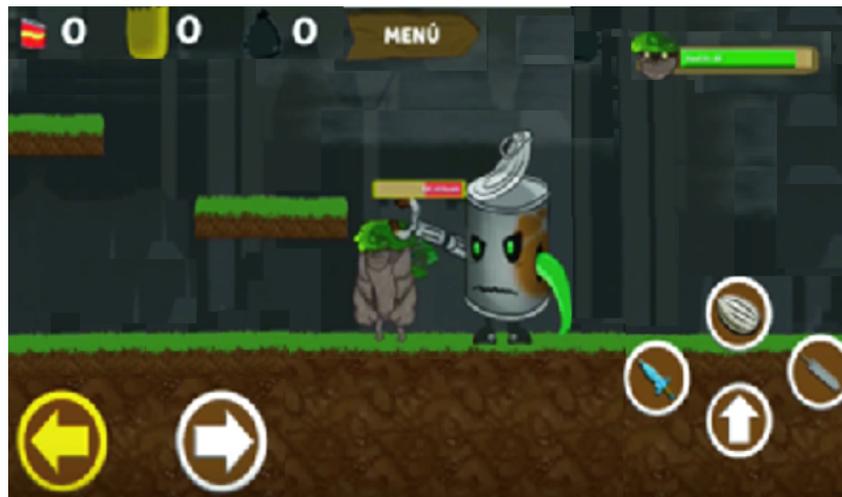
Figure 4. *Wood of War* encourages players to map trash by using real-world data to spawn trash monsters (Adapted with permission from Ref. [7]).

Other gamified software for waste management is the Multi-Agent-Based Modelling environment *NetLogo* [8] (Figure 5), developed in 1997 by Professor Uri Wilensky at the Center of Connected Learning (CCL) at Tufts University. This programmable software has been used in the modeling process in different areas including teaching, education, and research.
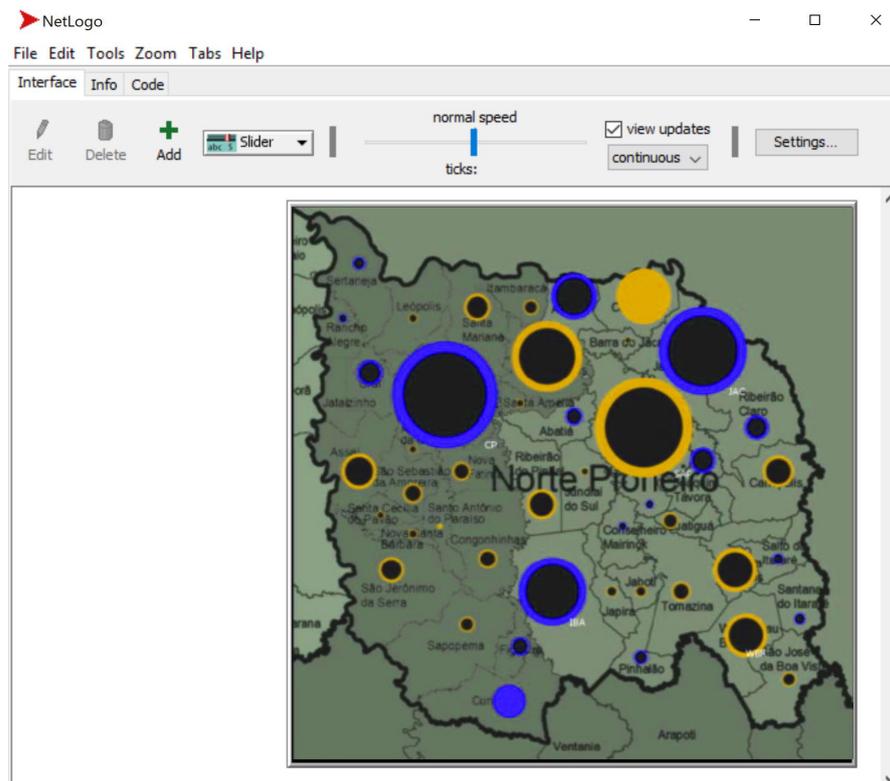
Figure 5. *NetLogo* was used to model and project waste management in the Norte Pioneiro region of Parana (Adapted with permission from Ref. [9]).

Eunice David Likotiko, Devotha Nyambo, and Joseph Mwangoka used *NetLogo* for the real-time simulation of waste management decisions. In the simulation, citizens are involved in optimizing the cost of waste collection services as well as providing decision algorithms to determine the best mobility for waste collections and bins. The authors'

model verified the optimal waste collection route, aiding the development of smart and innovative waste management systems and modeling for real life scenarios. Continuous empirical data and Geographical Information Systems (GIS) are proposed to be used for further model extensions [10].

Addressing sociotechnical aspects of waste management, Vitor Miranda de Souza et al. [9] used the dynamics of waste generation, disposal and collection to assess the eco-effectiveness of a solid waste management plan using *NetLogo*. The authors assessed the eco-effectiveness of Parana's Norte Pioneiro region, forecasting waste generation, collection, and other waste management processes. Different population growth scenarios were simulated from 2020–2038, with different criteria analyzed to generate success metrics. This illustrates how *NetLogo* and similar ABMs may be used to inform socio-technical and socio-economic aspects of waste management plans as well as model the influence of policy [9].

In Table 1, we summarize these representative games or gamified tools and showcase their approach towards waste management.

Table 1. Comparison of waste grouping, disposal methods, notification methods, and use cases for Waste Management Systems in Gamified Tools and Commercial Games.

Commercial Games /Research Tools	Information About Waste Management Systems
SimCity 4	All waste lumped as "garbage"
	Multiple disposal avenues (Landfill, Recycling, Waste-to-Energy)
	Waste accumulation reported though desirability reports, Mayor Rating
Cities: Skylines	All waste lumped as "garbage"
	Multiple disposal avenues (Landfill, Recycling, Incinerator, Waste Processing, ...)
	Waste accumulation reported though feedback bubbles
Wu and Huang's Research Tool [6]	All waste lumped as "garbage"
	Multiple disposal avenues (Waste Product Dump, Incinerator, Environment Factory, Trading Companies)
	Waste accumulation reported though reports of garbage-driven natural disasters
Wood of War	Multiple waste monsters found with varied garbage piles
	Waste disposed of by defeating monsters Real-world waste reported through GPS tags
	Real-world waste build-up is communicated to developers, authorities
NetLogo	All waste types lumped
	Sociotechnical approach for complex waste management and decision-making
	Waste management parameters (agents) executed serially. Empirical calibration necessary to mirror real-world scenarios.

A clear opportunity remains to develop a tool that combines gamification and ease-of-use with robust simulation and easy-to-read performance metrics to provide a quick feedback loop relating to policy and other changes.

3. Factors Affecting Waste—Key Performance Indicators

Waste management tools are important to informing policy and educating the public about the consequences of waste and necessary remediation. Here, we evaluate critical waste parameters as a means of identifying the policy and procedural "levers" suitable for changing certain key metrics. We will use the developed metrics and models as the basis for the development of our novel waste management simulator.

3.1. Approaching the Waste Management Problem

Waste management modelling takes the form of a multi-criteria decision-making problem comprised of multiple variables. The general form of this kind of problems is expressed in Equation (1):

$$min\textbf{\textit{y}} = F(\textbf{\textit{x}}) = \{f_1(\textbf{\textit{x}}), \dots, f_n(\textbf{\textit{x}})\}$$
$$where \ \textbf{\textit{x}} = (x_1, \dots, x_m) \in \textbf{\textit{X}} \tag{1}$$
$$\textbf{\textit{y}} = (y_1, \dots, y_n) \in \textbf{\textit{Y}}$$

$F(\textbf{\textit{x}})$ represents multiple functions–relations (e.g., $f_1(x)$), x represents measurable value variables and y represents the possible multiple results. The variables x_i can be discrete or continuous variables that belong to the bounded set $\textbf{\textit{X}}$. In the real world, there are no infinite values of measurements, thus $f(x)$ factors need to be bounded. Similarly, y_j represents the possible measurements of results.

To solve this type of problem, which is equal to finding their minimum (optimization), there are multiple methods—each one with pros and cons such as linear programming, ELECTRE methods, NSGA-II, and SPEA2. In our case, we formulate the optimization of the waste management problem:

$$min\textbf{\textit{y}} = F(\textbf{\textit{x}}) = \sum_{i=1}^{n} w_i f_i(x) \tag{2}$$

The weights w_i represent the values that each factor $f_i(x)$ affects the waste management problem.

One possible waste management optimization could potentially approximate the "Green City" target. The cities, according to the "Green City" targets, tackle the most urgent environmental challenges involving five key areas: air, water, nature and biodiversity, circular economy and waste, and, lastly, noise. Mayors agreeing to the "Green City' targets must establish ambitious plans over-exceeding the requirements of the EU laws and implement policies to achieve those by 2030 [11]. However, this optimization is hard or impossible to solve as a unified solution since it may involve factors that are both measurable and non-measurable, such as human behavior or unanticipated environmental consequences. Some may be measured using field research techniques in real time (measurable variables), whereas others may require approximation. This may necessitate measuring the indirect effects of lesser-qualitative factors, such as policy changes, over time.

Based on the team's prior field research [12–16], we present what we believe to be the most crucial and measurable factors in waste management to inform the design and development of a waste management tool (as described in Section 4). This way, we are trying to model an approximation of the problem, but not optimize it, as our first step. These factors are the Key Performance Indicators and are showcased in Section 3.2.

3.2. Key Performance Indicators

Waste management systems are becoming more complex as regions shift from landfill to resource recovery-based solutions. This shift requires authorities to have information concerning different aspects of waste management in order to develop plausible models and actionable solutions [13]. The discovery of realistic and consistent data can be established through the use of Key Performance Indicators (KPIs) originating from real-world data

collection. The purpose of these KPIs is to simplify assessing the perceived outcome of waste management within a virtual city in order to provide quantifiable evidence of performance [12].

The KPIs chosen to create a realistic user interface for the virtual city are amongst those widely used in waste management analysis [12,13,15–19] and include: Waste Compositional Analysis (MSW-C), Municipal Solid Waste Production (MSW-P), Municipal Solid Waste Recycling (MSW-R), Waste Production Rate (WPR), Waste Recovery Rate (WRR), Generation Rate (WGR), Waste Infrastructure (WI), Clean Index (CI), Accumulation Rate (AR) and Accumulation Index (AI), Mobility, Renewable Energy, Waste Water Treatment Plant, Air Pollution, and Strategies.

3.2.1. Waste Compositional Analysis(MSW-C)

MSW-C provides the data pertaining to the several produced waste streams, providing authorities with measurable data to design and implement waste prevention and waste management strategies [13,18]. MSW-C categorizes the types of material in solid waste such as PMD, Plastic Film, non-recyclable Plastic, Aluminium and Ferrous objects, Paper, Glass, Toilet and Kitchen Papers, Edible Food Waste, Inedible Food Waste, Organic Waste, and other materials [13]. To provide a representative baseline for the creation of a novel waste management simulator, a study in the Area of Paralimni, Cyprus was used. In the study, according to the population of the area in 2011 (18,601 residents), 15,100,000 tonnes of municipal solid waste were produced [12,13,15]. According to the compositional analysis carried out for the population of 18,601, the numbers were scaled to reflect the population of the virtual city (100,000). The estimated amount of each type of waste as scaled up for the virtual city is shown in Table 2.

Table 2. Waste Compositional Analysis categories, percent relative range and scaled amount of Waste for the virtual City.

Categories of Waste	Range (%)	Scaled Estimated Amount (tn)
PMD	5–30	7639
Plastic Film	1–7	3588
Plastics Non-Recyclable	1–3	1835
Aluminium/Ferrous	0.5–2	682
Paper	5–20	8572
Glass	1–7	4327
Toilet and Kitchen Paper	1–15	9652
Food Waste (edible)	2–20	12,055
Food Waste (inedible)	2–20	4091
Organic Waste(Green Waste, Yard Waste)	2–20	22,243
Others	1–10	6494
	Total	81,178 (figures per [13])

MSW-C is defined in Equation (3). The equation presents the ratio of the known reported amount of each category of MSW($Q_{knownMSW}$) to the total amount of MSW($Q_{TotalMSW}$) at a given time(t) [18]:

$$MSW - C = \frac{Q_{knownMSW}(t)}{Q_{TotalMSW}(t)} \tag{3}$$

The values are adapted from [13].

3.2.2. Municipal Solid Waste Production(MSW-P)

MSW-P represents the ratio of the amount of MSW produced (Q_{Tot}) to the population (*POP*) at a given time (*t*) in the selected area (see Equation (4)). This indicator delivers a

ratio of the average waste quantity per capita [12,15,18]. City geometry and population determine the range of this number:

$$MSW - P = \frac{Q_{Tot}(t)}{Q_{POP}(t)} \tag{4}$$

3.2.3. Municipal Solid Waste Recycling (MSW-R)

MSW-R measures the MSW that has been recycled (Q*RecycledMSW*) in comparison with the total solid waste produced (Q*TotalMSW*) at a moment in time (*t*), per Equation (5). Table 3 presents the categories of the recycled waste which are PMDs, Paper and Glass [12,13,16]. These numbers will be useful in the strategic planning of Waste Management Systems, give information on the prevention activities performed in each area as well as provide data regarding the technical aspects of Waste Management like Waste Bin Capacity, types of Recycle Bins in each area, etc. [12]:

$$MSW - R = \frac{Q_{RecycledMSW}(t)}{Q_{TotalMSW}(t)} \tag{5}$$

The data used in Table 3 were obtained from www.greendot.com.cy, accessed on 24 October 2021, and reflect figures for Paralimni, Cyprus in 2011 as scaled to fit the virtual city's population of 100,000 [20]. Green Dot Cyprus Public Co Ltd. is a non-profit organization and the first collective recycling system approved by the Ministry of Agriculture, Rural Development and Environment in Cyprus. It is established based on the Packaging and Waste Packaging (Amendment) Law, 2005 (Law No. 159(I)/2005) of Cyprus and implemented based on Directive 2003/35/EC of the European Parliament and the Council of the European Union [21,22].

Table 3. Municipal Solid Waste Recycling Categories and Range.

Categories	Range (%)	Estimated Amount (tn)
PMD	50–100	3819
Paper	50–100	4286
Glass	80–100	3461
Total		5172

3.2.4. Waste Production Rate (WPR)

WPR illustrates fluctuations in the volume of waste produced annually. These fluctuations inform the actions necessary to minimize waste production increases [12,18]. With the use of WPR, a possible percentage of achievement until a given time can be evaluated. WPR can be calculated using Equation (6):

$$WPR = \frac{Q_{total\ waste\ production\ next\ year}(t)}{Q_{total\ waste\ production\ previous\ year}(t)} \tag{6}$$

3.2.5. Waste Recovery Rate (WRR)

WRR indicates the recovery of generated waste in a specific period (Equation (7)). Numerous recovery options are available, including recycling, reuse, waste to energy, etc. WRR should not be misinterpreted for MSW-R, as waste stream recycling states the actual percentage of recycled material in a particular area with a specific population density, whereas WRR refers to the potential of recovering 100% of any significant waste stream like plastic, paper, etc. Waste recovery informs waste prevention strategies to reach the full potential of recovery of a stream [12,16,23]. The recovery rate of each material is listed in Table 4:

$$WRR = \frac{RecoveredWaste}{MSW - P} \tag{7}$$

Table 4. Typical municipal solid waste recovery rates.

Categories	Range of Recovery (%)		Estimated Waste Recovered (tn)
	Min	**Max**	
PMD	50	100	3819
Aluminium/Ferrous	50	100	341
Paper	50	100	4286
Glass	80	100	3461
Food waste	50	100	8073
Green Waste	80	100	17,794
			37,776

3.2.6. Waste Generation Rate (WGR)

WGR estimates the generation of waste in the selected area in unit of time (i.e., per day, week, month, or year) and is represented by Equation (8) [16,24]. As product and service demands increase along with economic and population growth, waste generation is inevitable. World waste production was estimated at approximately 1.30 billion tonnes in 2012 and by 2016 waste generation reached 2.01 billion tonnes of waste. If waste generation continues in the same trajectory, by 2050, this number is estimated to reach on average 3.40 billion tonnes of waste [25,26]. The indicator provides an assessment of an area's ecological trends as well as showcase the effectiveness of any sustainability practises and strategies implemented in that area according to the increase or decrease of its value.

WGR will vary with the population density of each selected area in the virtual city. As the total quantity of waste produced for the 100,000 citizens is 65,000 tones, an average citizen will produce 650 kg/year.

$$WGR = (Waste\ production\ in\ one\ area\ (kg)) \times (Citizens\ in\ the\ same\ area\ in\ one\ day) \tag{8}$$

3.2.7. Waste Infrastructure (WI)

A crucial indicator (Equation (9)) concerning environmental performance is the available waste management infrastructure. WI estimates without limitation the number of bins and collection bins in general in a specific area. It provides useful information about the current infrastructure in relation to the residential density of that area [12,13,16].

Depending on area, the user will be able to choose from one to all the bins listed in Table 5. WI depends strongly on the population density; as population density increases, the number of bins will increase proportionally. Depending on the user's choice, the outcome will be different. For population density of 100,000 citizens and 65,000 tones of waste, 750 bins are required. This indicator provides useful information to inform policies and actions required in relation to the existing infrastructure and number of citizens [12,13].

$$W.I = \frac{\#\ of\ bins}{Population\ density} \tag{9}$$

The range of recycle bins per population density must comply with the requirements of the level of services presented in Section 3.2.8. The minimum range of waste bin capacity must be the minimum 0.5–1.5 L/capita in line with 3(C) and maximum/over 1.5–2.5 L/capita as mentioned in level 1(A) in Table 6 [12,15].

Table 5. Types of recycling bins proposed range per population density and range.

Categories	Bin Colour	Proposed Range
Recycle Bin for:		
Plastics	Yellow	
Paper	Brown	
PMD	Blue	min: $W.I \geqslant 0.5$–1.5 L/capita
Mixed waste	Green	max: $W.I \geqslant 1.5$–25 L/capita
Food Waste	Pink	
Green Waste	Light Green	
Batteries	Transparent	
Glass Packaging	Grey	
Aluminium	Perforated	

3.2.8. Clean Index (CI)

CI rates how clean the selected area is using Equation (10), where NI_{col} is the number of items collected (i.e., cigarette butts, PMD, papers, other plastics, etc.) and Sur is the surface in m^2 of the specific selected area. K is a constant equalling 20 [12,15,16,27].

Table 6 is used to scale the area accordingly [16]. Using CI, the infrastructure of the selected area can be assessed to optimize activities including waste collection period, cleaning department size, number of recycling bins per citizen, etc. The indicator was first suggested by Alkalay [27]:

$$C.I = \frac{NI_{col}}{Sur} K \tag{10}$$

According to [12,15,16], the Level of Services (LoS) may be interpreted as:

- **1(A)**: Outstanding waste collection, defined as at least three times daily (morning, midday, afternoon). Waste bins exist at least every 100–200 m as well as other waste infrastructure (such as separated recycling bins, collection of hazardous waste, or increased waste awareness and informational signs). Mechanical cleaning of roads two times weekly, with waste bin capacity at least in the range of 1.5–2.5 L/guest.
- **2(B)**: Acceptable collection of waste, three to four times/week and twice/day for some areas (e.g., morning and afternoon collection, average waste bin separation of 200–400 m with other waste infrastructure (e.g., recycling bins). Waste bins capacity is at least 1.0–1.4 L/visitor. Informational signs are visible, and mechanical road cleaning occurs at least weekly.
- **3(C)**: Average collection of waste twice weekly and once per day in some areas. On average, waste bins are spaced ever 500 m with some other waste infrastructure available. Waste bin capacity varies from 0.5–1.4 L/visitor with limited awareness and informational signs, with only periodic road cleaning.
- **4(D)**: Periodic collection of waste–approximately once weekly, with limited public waste bins or other infrastructure, zero implementation of mechanical cleaning of the roads and waste bin capacity 0.5–1.4 L/visitor.
- **5(E)**: Zero formal cleaning programs in the area, no waste infrastructure and no mechanical cleaning of the roads. Little to no waste awareness or signage.

Table 6. Clean Index Identification.

Quality	Level of Sevices (LOS)	CI	Identification
Very Clean	1(A)	0–2	No litter seen
Clean	2(B)	2–5	No litter seen over a large area
Moderate	3(C)	5–10	A few pieces of litter visible
Dirty	4(D)	10–20	A lot of litter visible
Very Dirty	5(E)	20+	Most of the area is covered in litter

3.2.9. Accumulation Rate (AR)

AR evaluates the accumulation of waste per unit of surface area and unit time (items/m^2/day) (Equation (11)) [12,13,17]. AR is directly affected by population density as, consequently, the more people there are in an area, the more waste will exist [28]. *T* represents the time elapsed between the survey and the last cleaning activity which also gives an indication of the number of days since the responsible authority completed a full cleaning of the researched area [29]:

$$A.R = NI_{col}/S/T \tag{11}$$

3.2.10. Accumulation Index (AI)

AI takes into account the rate of accumulation of liter (Equation (12)), complementing CI and AR. While CI assesses area cleanness and hence the collection period, AI and AR evaluate the accumulation of waste at a given area in a specific period [15]. Table 7 represents the classification given by [16]:

$$A.I = log10(A.R \times 1000000) \tag{12}$$

LOS is explained in Table 6.

Table 7. Accumulation rate and index classification.

	LOS	WAI	WAR (items/m^2/day)	WAR (items/km^2/day)
Extremely Low	1	≤1	0.000001	1
Very Low	2	1–2	0.00001	10
Low	2–3	2–3	0.0001	100
Moderate	3	3–4	0.001	1000
High	4	4–5	0.01	10,000
Very High	4–5	5–6	0.1	100,000
Extremely High	5	≥6	1	1,000,000

3.2.11. Air Pollution

Air Quality Indication (AQI) illustrates the gas emissions in the virtual city including simulated CO_2, CO, NO, NO_2, SO_2, O_3 and Benzene as shown in Table 8. The correlation of air pollution with human activity is of significant interest, and are driven by emission sources like vehicles and industrial processes [30]. Greenhouse gas emissions from solid waste treatment emerge mainly from uncontrolled disposal and dumping as well as incineration [26].

The urbanization of the last 60 years has created high transportation network density, encouraged building development, and driven population growth that promote the consumption of variously-sourced energy sources and energy in general while the lifestyle in urban environments make the application of environmentally conscious actions appear to be a far off necessity rather than a personal responsibility [31]. Air quality management is vital to both protect human health and improve the quality of life in urban and industrial areas [32]. Strategies to better handle waste management can decrease greenhouse gas emissions by as much as 200 million tonnes by 2030 [26,33].

The limits were provided considering the existing proposed limits by www.airquality .dli.mlsi.gov.cy/, (accessed on 24 October 2021) presenting the pollutants concentration values in Cyprus in real time. The results can be easily accessed from the official Air Quality Cyprus mobile application [34].

Table 8. Gas emissions observed.

Categories	Range (%)	Low	Moderate	High	Very High
PM_{10}	0–100	0–50	50–100	100–200	>200
$PM_{2.5}$	0–100	0–25	25–50	50–100	>100
Carbon Dioxide (CO_2)			To be defined		
Carbon Monoxide (CO)	0–100	0–7000	7000–15,000	15,000–20,000	>20,000
Nitrogen Monoxide (NO)	0–100				
Nitrogen Dioxide (NO_2)	0–100	0–100	100–150	150–200	>200
Sulphur Dioxide (SO_2)	0–100	0–150	150–250	250–350	>350
Ozone (O_3)	0–100	0–100	100–140	140–180	>180
Benzene (C_6H_6)	0–100	0–5	5–10	10–15	>15

3.2.12. Mobility

The Mobility metric indicates the public transportation available for a given population density. Mobility is directly interlinked with fuel consumption and greenhouse gas emissions. This indicator helps authorities explore new innovative mobility plan strategies in order to limit the environmental impact of transportation, especially in urban areas [35]. The use of public transportation in the simulation versus the choice of the user to transfer by car will make a crucial difference regarding gas emissions. The choices of public transportation offered in the virtual city are listed in Table 9.

Table 9. Available transportation choices.

Transportation
Buses
Trams/Trolleys
Trains/Underground Metro
Bike lanes
Walk lanes
Electric Cars

Important criteria for the selection of Mobility transportation Choices should be when applicable:

- **[A]** Public Transportation must line with existing EU regulations regarding Transportation means (i.e., 80% Electric Cars by 2050 [36])
- **[B]** They must cover existing National plans and targets.
- **[C]** Satisfy the needs of Public Transportation for the maximum population density requirements.
- **[D]** Contribute to the existing National Plans to reduce Carbon Dioxide emissions.

3.2.13. Green Space

The Green Space KPI denotes free green space per population density in m^2 or km^2 (Equation (13)). Green spaces include parks, open-air sport facilities, playgrounds, etc. [37].

Strategic urban planning for land management encourages good living conditions due to psychological factors and also the reduction of the environmental impact of urban areas [38]. Natural and semi-natural areas designed in urban cities serve not only recreational and aesthetic stress reducing purposes but provide an improved living environment. This is achieved by natural processes in the presence of biodiverse green spaces like purifying the air and water, providing protection from extreme weather conditions like heat and thunderstorms, and also contributing to the reduction of noise pollution [39].

The strategic distribution of green areas across the virtual city is essential in order for all the citizens to have access to these green spaces. Therefore, Green Space must be closely coupled to population density as well available public free space.

Table 10 indicates the choices of the user regarding green space categories. The limits were chosen according to the recommendations of the World Health Organization [40,41].

$$GreenSpace = \frac{Free\ green\ space}{Population\ density} \tag{13}$$

Table 10. Green space requirements per capita.

Green Space Categories	Green Space Requirements (m³/capita)
Green Space (Parks, Playgrounds, Open-air Sport Facilities)	min: 9 m³/capita optimum: 50–57 m³/capita

3.2.14. Renewable Energy Sources (RES)

Fossil fuels have been a primary energy source for cities for decades. Wasteful handling of raw materials, food, and energy made necessary the creation of innovative renewable energy technologies [42]. The use of renewable energy sources, coupled with emerging energy storage technologies, may present a more balanced approach towards sustainable socioeconomic development and prosperity [43]. Production of renewable domestic energy is of interest as a means of managing the need for raw materials that each technology requires [43,44].

The RES available are listed in Table 11, calculated per population density or km². The available categories of RES and the percentage they hold in the Total Energy production are Photovoltaic (P/V) Parks (1–5%), P/V Houses (5–100%), and Wind Parks (1–4%) according to the Transmission System Operator Cyprus for the year 2020 and the Cyprus Energy Regulatory Authority [45,46]. The indicator measures the number of RES in place and national targets.

Table 11. Renewable Energy Sources percentage share in Total Energy Production.

Category	RES Share in Total Energy Production (MWh)
RES (P/V Parks, P/V houses, Wind Parks)	min: 11.7% (63,176 MWh) max ≥ 32% (≥114,760 MWh)

Data provided by the Transmission System Operator Cyprus for the year 2020 and the Cyprus Energy Regulatory Authority [45,46]. The data collected concerned the population of Cyprus of 888,000 citizens for 2019 and were scaled down for the 100,000 of the virtual city [47]. The optimum maximum limit of 32% of Renewable Energy Sources in Total Energy Production is derived from the Policy framework of the European Commission in 2014 for 2030 [48].

3.2.15. Waste Water Treatment (WWT)

Urban wastewater management constitutes a challenging topic due to poor synchronization among infrastructure development and population growth. The main concern of Waste Water Treatment is to protect the environment and specifically the surface of waters from organic pollution and the degradation of aquatic life as well as the protection of human health [49]. In real life situations, agglomerations and collection systems provide a much more provable approach regarding the level of treatment of wastewater. Agglomerations, referred to as a sufficiently concentrated area for wastewater to be collected and further conducted to a nearby treatment plant, are usually required to be sufficient for a number of populations equivalent (1 Population Equivalent (P.E) unit is the organic biodegradable load of having a five-day biochemical oxygen demand (BOD5) of 60 g of oxygen per

day) [50]. The Urban Waste Water Treatment Directive (WWTD) which is directly linked to zero waste ambitions in the European Green Deal requires all European settlements to provide their cities with agglomerations of the size of 2000 population equivalents or above and equipment (i.e., Collection systems, Wastewater Treatment Plants) sufficient for the waste water [51].

In this section, the indicator of Equation (14) presents only the number of houses connected to the waste water treatment plant with a range of values from 0–100% [52]. This range submerges from data of Eurostat% [53], where, until 2018, Denmark, Latvia, France, Malta, Finland, Austria, and the Netherlands had a 100% of their population connected to a Wastewater Treatment facility, whereas Kosovo maintained only a 0.52% of the population connected to wastewater treatment with the very next being Serbia with 14.12. Due to the fact that the quality of wastewater treatment emerges from the level of treatment (Primary, Secondary, Tertiary) as well as the available infrastructure mentioned above (Agglomerations and collection system), the indicator will be used regarding the following conditions:

- **[A]** The wastewater treatment plant will perform all primary, secondary, and tertiary treatment [50].
- **[B]** Agglomerations and collection systems are 100% treated in the wastewater treatment plant.
- **[C]** The P.E of each area will always be within the limits provided by WWTD ($\geq$2000 P.E).
- **[D]** Wastewater Treatment plants will protect environment and surface waters as well as human health [49]:

$$W.W.T = \frac{connected\ population}{total\ population} \times 100. \tag{14}$$

3.2.16. Strategies

Seeking to grow a sustainable world has necessarily increased the strategic relevance of waste prevention [54]. To reduce the impact of industrial processes that affect severely the environment, corporate policies must be set in place. The main focus of waste prevention strategies is the reduction of landfill material, resource saving, the protection of human health, and improved quality of life by sustainable economic development [14,18]. Strategies available include circular economy, the European Green Deal, the United Nations Sustainability Goals, Zero Waste Policy, Energy Recovery, Smart Cities, Environmental Management Systems, and R-strategies [12,28,43,55–57]. Strategies like these, effectively implemented, will create a social shift in attitude that is vital to the success of any policy or indicator. Table 12 illustrates the user's available choices [16,43].

Table 12. Strategies for action.

Categories
Circular Economy
European Green Deal (EGD)
United Nations Sustainability Goals (UNSDGs)
Zero Waste Policy
Low Carbon Society
Waste Prevention
Energy Recovery
Smart City
Environmental Management Systems (i.e., ISO14001, EMAS)
R-strategies

Corporate policies, such as ISO 14001, EMAS, zero waste, etc., can reduce the impact of industrial processes on the environment by limiting energy requirements, im-

proving waste water treatment processes, and increasing the social acceptance of such initiatives [12,16,28,43,55–57].

At the same time, alternative energy scenarios which revolve around renewable energy resources and/or energy recovery ensure the supply of reliable and efficient energy and utilisation [58]. The emissions related to fossil fuels combined with climate change have already forced many countries worldwide to explore strategies for better energy sources compared to the global energy mix [59]. The transition to clean renewable energy and zero emissions can be enabled by a shift to a more circular economy [43].

The concept of a Circular Economy (CE) is powerful tool many social groups including policy makers, urban designers, and academics employ to fundamentally link resource use with waste. CE is recognized by the European Union as an "irreversible global mega trend" and is now an essential strategy for the accomplishment of the goals set in the European Green Deal [43,60]. The shift from a linear to circular approach can result in the implementation of environmental and economic policies in order to achieve waste prevention, reuse, and recycling which directly contributes to clean production and manufacturing. This creates a stronger economy where resources are used in a more sustainable way [12,24].

An important category included in strategic sustainable development are the prevention activities carried out by individuals or groups of people in a social structure. The awareness activities related to waste prevention practices like reuse, recycling, refurbishment, and material recovery are important for the successful transition to a sustainable, environmentally acceptable development. Both domestic and industrial changes can lead to the reduction of greenhouse gas emissions and to the development of new waste treatment concepts [12,61].

The secret to waste prevention plans and to the implementation of strategies like these is social behaviour and acceptance [14]. A broad-based willingness to contribute to sustainable development is the fastest way to meet the standards and targets set by the policy makers and urban developers [18]. While the behavior regarding household waste prevention activities has been explored mostly on a qualitative rather than quantitative level, activities focusing on the reduction of waste and thoughtful use of everyday products are likely to reduce landfill waste [14,62]. It is vital for citizens to understand that waste prevention is everybody's responsibility and taking thoughtful actions before an item becomes waste is an essential step to meet the sustainability standards [12].

Actions like these are presented in Table 13 where the available categories to assess any prevention activities are introduced, e.g., food waste reduction or participation in home composting, participation in web-platforms related with waste management in household level, etc. [13].

Table 13. Prevention activities.

Categories
Use of leftovers
Use of reusable Grocery Bags
Reusable Coffee Cup
Home Composting
Food Waste Campaign
Donations where possible (i.e., Toys,Books,clothes etc)
Book exchanges
Smart shopping list (buying exact necessities from stores)
Keeping vegetables and fruits in loosely tied bags
Reuse of electrical appliances
Electrical Appliances repair stores to extend life time of devices

3.2.17. Correlations among KPIs

When researching the Environmental Performance of an area, correlating the Key Performance Indicators reveals scenario-dependent interaction. Table 14 offers a brief

qualitative approach to codify these correlations that, with methodological analysis, may lead to not only qualitative but also quantitative assessment of an area's sustainability by addressing connections and dependencies between the indicators for the creation of links on waste management systems [63].

Table 14. Proposed Correlations between KPIs which will be defined through research at field and software such as lifecycle assessment, or other simulation tools.

	MSW-C	MSW-P	MSW-R	WPR	WRR	WGR	WI	CI	AR	AI	Air Pollution	Mobility	Green Space	Renewable Energy	Waste Water Treatment Plant	Strategies
MSW-C		✓	✓	✓	✓	✓										✓
MSW-P	✓		✓	✓	✓	✓										✓
MSW-R	✓	✓		✓	✓	✓	✓									✓
WPR	✓	✓	✓		✓	✓	✓								✓	✓
WRR			✓			✓	✓									✓
WGR	✓	✓	✓	✓	✓		✓	✓	✓		✓					✓
WI	✓		✓			✓							✓			✓
CI	✓					✓	✓		✓	✓	✓		✓			✓
AR	✓					✓	✓	✓		✓						✓
AI	✓					✓	✓	✓	✓							✓
Air Pollution	✓					✓			✓	✓		✓	✓		✓	✓
Mobility											✓		✓			✓
Green Space							✓	✓	✓	✓	✓	✓				✓
Renewable Energy	✓					✓					✓	✓			✓	✓
Waste Water Treatment Plant																✓
Strategies	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Acronyms and Terms																
MSW-C	Waste Compositional Analysis															
MSW-P	Municipal Solid Waste Production															
MSW-R	Municipal Solid Waste Recycling															
WPR	Waste Production Rate															
WRR	Waste Recovery Rate															
WGR	Waste Generation Rate															
WI	Waste Infrastructure															
CI	Clean Index															
AR	Accumulation Rate															
AI	Accumulation Index															

4. Design and Development of Waste Management Tool

Once we had identified and selected critical KPIs (Section 3), we proceeded to design and develop an interactive Waste Management Tool suitable for education and informing policy. The concept was to create an application that can help students understand the challenges associated with waste management, and guide them through learning about KPIs that affect waste management systems' performance. Gamification elements make the experience more engaging, interactive, and pedagogically "sticky" to encourage concept retention. In order to design the tool, we used Unity Game Engine and we purchased relevant low-polygon count 3D objects from the Unity Asset Store to accelerate development. The game interface is described in the following subsections.

4.1. Current Status of the Tool

In its current form, the tool comprises a main menu (Figure 6) and a main scene (Figure 7). The main menu enables users to transition to main playable scene or alternatively allows the user to showcase the credits or exit the game.

The main scene is the interactive core of this application. It features an imaginary virtual city with population of 100,000 people that is comprised of nine areas laid out in a 3×3 matrix (Figure 7). Each area has unique and distinct parameters that may be randomly defined or tuned related to waste generation and management. When the main scene is loaded, the player camera moves from a close-up view to a top-down perspective to allow an overview of the entire city in a single window. From this top-down view, players are able to select and engage with the various interactive areas and elements of the city.

Upon loading the main scene, each area is automatically assigned with a random population number out of specific options. These options are 1500, 2000, 5000, 6500, 7000, 10,000, 18,000, 20,000, and 30,000 to sum to 100,000. The total population of 100,000 people helps to simplify calculations for the user. The graphics and the building models including

houses do not reflect the numbers of the area population assigned but are representative and increase user engagement and relatability. In Figure 7, we see that the population of $Area_{11}$ was automatically set to 2000 people by the tool. The rest areas were assigned with each area having the value of one of the remaining choices from the options list.

Figure 6. The Waste Management Tool's main menu allows players to start the simulator, view the credits, or exit the game.
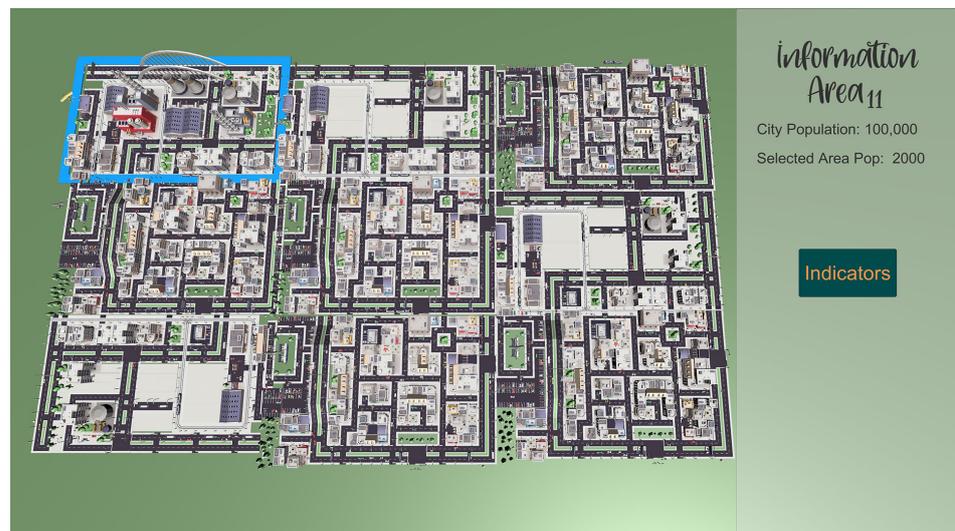

Figure 7. The Main Scene features a top-down view of the city, divided into nine parts. Each part can be highlighted, selected, and clicked to view information about waste management KPIs and policies in that region.

Having selected a specific area of the virtual city, the users may press the "Indicators" button on the right side of their screen. After doing so, a panel with the indicators (Figure 8) for the selected area appears. These indicators are the same KPIs that we have identified and presented in Section 3.
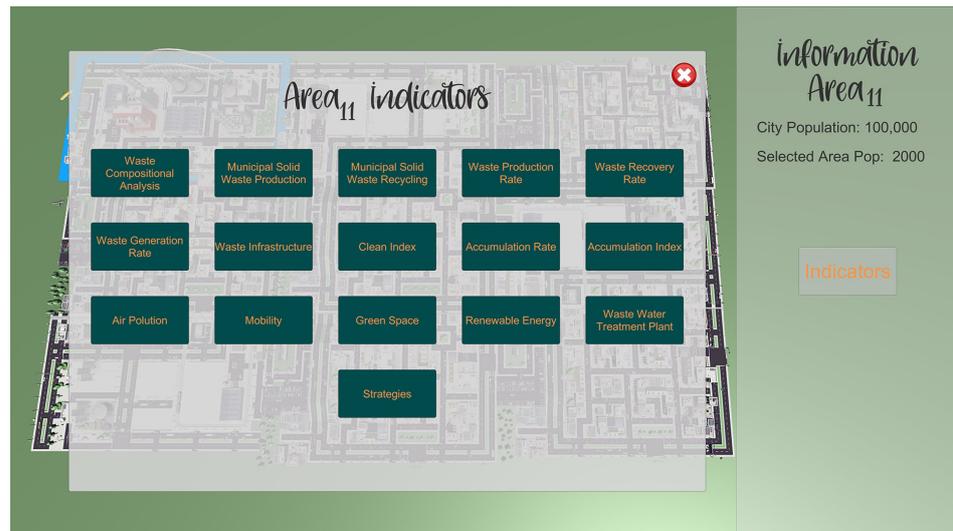
Figure 8. Key performance indicators for each region are shown on a dashboard to provide a high-level, easily interperable overview of waste management performance.

In this panel, the KPIs present new buttons that users can interact with. For illustrative purposes, we will explain how the first two indicators work. Starting with the Waste Compositional Analysis (MSW-C), this KPI is comprised of multiple configurable values each as described in Section 3.2.1. Using the amounts measured at Municipality of Paralimni and scaling up from 18,601 to 100,000 people for our simulator, we created Table 15 to display possible ranges in these categories for internal design purposes only. These amounts are scaled to fit each population option for all areas. The final bounds for each population option are presented in Table 16. These values are stored to an external and accessible file enabling easy customization in the case of new research developments necessitating specific game permutations.

Table 15. Waste Compositional Analysis categories for a population of 100,000 people and possible range in tn for each of the categories (figures per [13]). This table is used only for designing purposes and its amounts were later scaled to express the upper and lower bounds of each of the area population options.

Categories of Waste	Scaled Est. Amount (tn)	Range (tn)
PMD	7639	5000–10,000
Plastic Film	3588	2000–5000
Plastics Non-Recyclable	1835	1000–3000
Aluminium/Ferrous	682	500–1000
Paper	8572	6000–10,000
Glass	4327	3000–5000
Toilet and Kitchen Paper	9652	8000–11,000
Food Waste (edible)	12,055	10,000–14,000
Food Waste (inedible)	4091	3000–5000
Organic Waste (Green Waste, Yard Waste)	22,243	20,000–25,000
Others	6494	5000–7000

Table 16. The Lower and Upper Bounds for each of the categories for all population options. These values were scaled based on the range from Table 15.

	Population: 1500		Population: 2000		Population: 5000		Population: 6500		Population: 7000		Population: 10,000		Population: 18,000		Population: 20,000		Population: 30,000	
	Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound
PMD	750	1500	100	200	250	500	325	650	350	700	500	1000	900	1800	1000	2000	1500	3000
Plastic Film	300	750	40	100	100	250	130	325	140	350	200	500	360	900	400	1000	600	1500
Plastic Non Recyclable	150	450	20	60	50	150	65	195	70	210	100	300	180	540	200	600	300	900
Aluminun/ Ferrous	75	150	10	20	25	50	32	65	35	70	50	100	90	180	100	200	150	300
Paper	900	1500	120	200	300	500	390	650	420	700	600	1000	1080	1800	1200	2000	1800	3000
Glass	450	750	60	100	150	250	195	325	210	350	300	500	540	900	600	1000	900	1500
Toilet and Kitchen paper	1200	1650	160	220	400	550	520	715	560	770	800	1100	1440	1980	1600	2200	2400	3300
Food Waste Edible	1500	2100	200	280	500	700	650	910	700	980	1000	1400	1800	2520	2000	2800	3000	4200
Food Waste Inedible	450	750	60	100	150	250	195	325	210	350	300	500	540	900	600	1000	900	1500
Organic Waste	3000	3750	400	500	1000	1250	1300	1625	1400	1750	2000	2500	3600	4500	4000	5000	6000	7500
Others	750	1050	100	140	250	350	325	455	350	490	500	700	900	1260	1000	1400	1500	2100

Similar to the area populations, the tool automatically loads the lower and upper bounds for the relevant population number. At the same time, it randomly sets a new value in the respective sliders for each category, creating a unique but broadly-similar city waste footprint for each user. A representative example for $Area_{11}$ is showcased in Figure 9. Users may then choose to change these values.
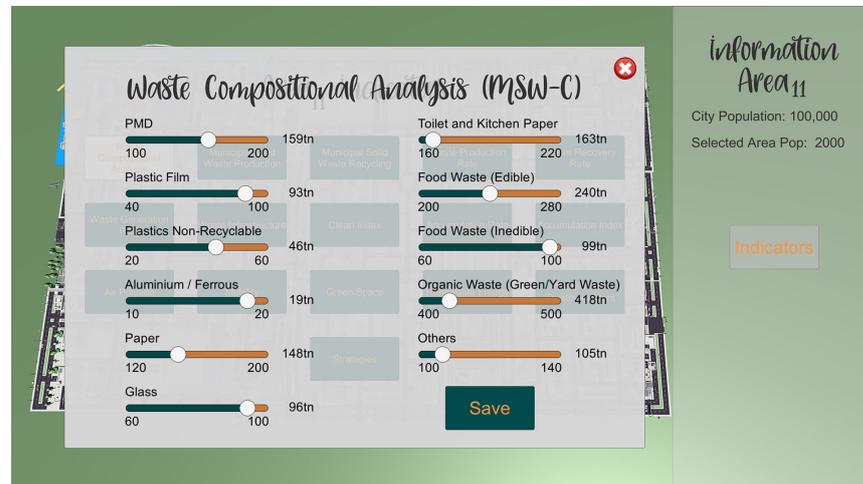

Figure 9. Each area's waste generation and policy parameters can be altered independently.

Next, we have the Municipal Solid Waste Production KPI (MSW-P). This KPI does not have any user-configurable categories and is completely independent of MSW-C. This value comes from the division of the total amount of waste divided by the population of the area, as shown in Equation (4).

Based on the tool's randomly-generated amounts (Figure 9) and the population of $Area_{11}$, (2000), we have the following:

$$\frac{Q_{Tot}(t)}{Q_{POP}(t)} = \frac{159 + 93 + 46 + 19 + 148 + 96 + 163 + 240 + 99 + 418 + 105}{2000} = 0.793 \quad (15)$$

As we notice in Figure 10, the result is the same as the calculated one in Equation (15). This result can change in real time when a slider value from MSW-C panel is also changed.


Figure 10. Clicking each metric provides information about how it is calculated, which helps students learn to create effective management policies. These indicators reflect the parameters as identified in Section 3 (note that due to regional differences, the figure shows a comma rather than a period in the numeric text).

These examples are representative of how all models involved in the computation of waste production and management are handled in the game design.

Using these indicators, along with configurable elements thereof, allows individuals to use the game as a means of modelling waste generation and management. Through study and play, users may learn those metrics most affecting waste production and mitigation in order to inform effective policies for diverse scenarios.

With the game created and reflecting the model developed in Section 3, this tool will be used to enable a range of academic studies that will be the subject of future work. Ongoing work will conduct playtesting with diverse constituents, the feedback from which will be fed into a version of the game to be made freely available to researchers (please contact the authors for additional information).

5. Conclusions and Future Work

Waste management is a critical and growing challenge, particularly in urban environments. Observational data are some of the best ways to study waste management to devise effective policy and to raise individual awareness that may curb waste production. Existing tools are either oversimplified or too complex for individuals to pick up and play, so we developed a game meeting the opportunity of joining a robust multi-factor waste generation and management model with ease of use and clear, rapid feedback to users. In this educationally-focused tool [64–66], students and policymakers may engage with the waste chain of a virtual city, changing model parameters and observing their affect on waste management performance through the use of visible key performance indicators. The game itself is built upon a robustly-defined multi-criteria decision-making problem comprising multiple variables.

Compared with existing modelling approaches that either oversimplify or require complex setup and deep domain knowledge, this game is a "Pareto optimal" solution. It is a highly-detailed real-world planning tool that also does an excellent job relative to the effort involved in setting up and running the simulation. From easy-to-make changes and readily-visible indicators, the broad impact of generation and policy changes is clearly understood. Enhanced knowledge stemming from gameplay may therefore contribute towards the creation of enhanced social policies and constituent engagement in efforts to reduce and manage waste. Particularly, participants will leave playing the game having a better understanding of the challenges associated with waste management with gamifying elements such as clearly presented and easy-to-track KPIs making the experience memorable and enduring.

While today, waste data are simulated, future virtual cities may instead make use of real-world data from municipalities and other government agencies in real time using IoT [67] to showcase examples of effective—and suboptimal—performance.

The designed tool may be integrated with other game-based simulators [68,69] to help quantify and seek to reduce other negative externalities, such as vehicle emissions, using real-world automotive diagnostic data and solutions [70–72]. Real-world fault data may also be captured from mobile devices [73–79] as a means of informing simulation of fuel-wasting faults such that the transit planning strategies reflect true inefficiencies, while a broader game might even model how waste bin placement might impact pedestrian traffic [80] and efficiently mirror cities digitally and in real time [81]. Even industrial processes [82,83] may be mirrored with the aim of improving resource efficiency and reducing waste. In the consumer-facing world, there may be opportunities to mitigate significant healthcare and home-life related waste, for example by integrating gameified waste modelling with digitally-connected disposable smart devices such as diapers [84] to track and trace the true chain of custody and provenance of real-world waste.

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