Model Conceptualization for Sustainable Waste and Resource Management Policy Design in Low and Middle-Income Countries through Dynamic Modeling and Simulation

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Abstract

The article sets out to describe the first stages of conceptualization process initiated within the scope of an action research project in the field of waste and residual resource management in a large urban center of a low-income country. For the project it is important to test that the management concepts developed by the project have the potential of improving waste management in future megacities. This involves evaluating if when implemented, these technological solutions can contribute to the alleviation of the current problematic situation. Additionally, it is important for the project to find out to what extent could the performance (financial, socioeconomic, environmental, etc.) of the waste management system improve as a result from the implementation of the waste management strategies it proposed. For this purpose a set of simulation models is being conceptualized and developed using a modeling methodology (namely System Dynamics), which will allow evaluating how the waste management situation would evolve if a set of strategy options would be introduced. This would be done by comparing the future development of the system in the absence of the strategies (business as usual) with the development of the system in the presence of the strategies. The article presents the first results of model conceptualization and gives an outlook of the activities that will follow.

1. Introduction

The research project "IGNIS - Income Generation and Climate Protection by Valorising Municipal Solid Wastes in a Sustainable Way in Emerging Megacities" strives to develop a new concept for the improvement of waste management and the local environment while generating new workplaces, increasing general welfare, considering occupational safety and health and reducing greenhouse gas emissions. Funded by the German Ministry of Education and Research (BMBF) through it Future Megacities programme, the IGNIS project takes on a systemic research approach to resource recovery from wastes in large urban centres in developing countries by implementing the project in the Ethiopian capital, Addis Ababa. Within the scope of this project, modelling and simulation was chosen in order to test the potential effects of the introduction of decentralised waste treatment plants, their multiplication and upscaling on waste reduction, greenhouse gas emissions, and job creation in a future megacity[1]. This task was defined very vaguely, both methodologically and in terms of the specific outcomes, and it has been responsibility of the author, as part of the research team, to define these aspects and to implement the modelling process. It was clear though, that the resulting models should be flexible, easy to use, and allow for the simulation of different scenarios in order to test the viability of different solutions under the conditions of Addis Ababa.

2. Review of Modeling in Waste Management

In order to identify the most appropriate methodology to be applied in the project, a survey of different modeling approaches was carried out. In the past, the deficiencies in waste management have been attributed in part to the lack of adequate and sufficient data, as well as to the absence of adequate computational tools that assist planners. As a result, waste management has drawn the attention of different system analysis and modeling traditions, such as spreadsheet analysis, operations research, input-output models, which include material flow analysis (MFA) and life cycle assessment (LCA), process engineering models, and system dynamics. Abeliotis et al (2009) classify the models found in literature into three categories: based on applied mathematics (including statistical analysis, optimization, and simulation), ruled-based expert systems, and hybrid methods (e.g. LCA). Dewi et al (2010) classify the models they surveyed depending on the dimensions that the models address into cost based, environment impact based, and multi-criteria decision models (i.e. holistic assessment models). The goal of the most used modeling methods (i.e. optimization, multicriteria decision models, and LCA) has been to serve as a decision support system that helps calculate and/or evaluate the impacts or effects of a set of strategies, in order to facilitate the selection of the most appropriate or optimal strategy (i.e. parameter set). However, rooted underneath the use of these methods is, to a large extent, the assumption that the complexity of the waste management system can be overcome by having sufficient data, highly detailed models, and broad enough evaluation systems. Additionally, the development of these models is based on the proposition that the optimal or most appropriate strategy can be achieved in the real world now and in the future.

One explanation for the dominating characteristic of the most popular modeling methods in waste management (i.e. static, prescriptive, open-loop, linear models) traditionally waste management planning has been observed from a normative perspective i.e. how waste management should be. These models do

[1] According to the United Nations a megacity is an urban center with more than 10 million inhabitants.

not consider how resources constrain or enable a specific strategy, how soft or social variables play a role in the viability of a strategy, and how dynamic complexity (feedbacks, accumulations, non-linearities, and delays) control the temporal behavior of the system variables. However, in order to realistically test how the new strategies would improve the environmental, economic, and social performance of the waste management system, these aspects need to be represented by the model. Therefore, another modeling framework needed to be taken into consideration.

3. System Dynamics as the Method of Choice

As a result of the inability of other modeling methods to address the needs of the project, System Dynamics was analyzed. System dynamics modeling and simulation promised to be a powerful method to address the structural and dynamic complexity associated with waste management, as it accounts for feedbacks, accumulations, delays, and non-linearities within a system (Sterman, 2000). Especially, since system dynamics enables the representation of human agency and decision making in complex systems, its use in waste management planning can allow making the jump from the evaluation of normative statements (i.e. optimal strategies) to the testing of the viability and likelihood of policy implementation. However, waste management has been the focus of very few system dynamics modeling efforts. Moreover, in many cases the elegance and apparent simplicity of SD modeling tools have been taken advantage of, without respect for the method, and yielding models that do not address complex dynamic issues and their causes, but rather serve as a tool for point prediction and forecasting.

A short review of SD literature shows that the first application, by Randers and Meadows (1973), was on the dynamics of waste generation resulting at the end of the product lifetime and it helped test potential policy levers to reduce the generation of waste and increase resource recovery. Mashayekhi (1988 and 1993) modeled the transition in New York State from land disposal oriented waste management system towards incineration and recycling. Chung (1992) addressed the issue of market development for waste recycling, where information flows and coordination through government policies play a significant role in controlling instability and increasing capacity utilization. Moreover, Zamudio (1996) and Taylor (1999) applied systems modeling to recycling in automobile and paper industries. In 2008 Stave used SD modeling to engage stakeholders in the Los Angele’s solid waste management initiative. In the same year Yücel and Chiong Meza studied the feedback interactions underlying the waste management transition in the Netherlands. Finally, System Dynamics has been used to develop a coupled economic development and demographic growth framework, in order to determine how waste and resource management policies impact the economic growth (Cimren, Bassi, and Finksel, 2010). Although small in number, these applications of system dynamics illustrate the richness and complexity found in waste management as a social, ecological, and economic issue.

4. Shortcomings in Strategic Planning in Municipal Waste Management

Adequate planning of waste management is essential if communities and regions are to successfully address the challenge of sustainable development, including resource conservation, climate protection, and pollution prevention. However, planning is mostly limited to operational planning i.e. how to construct and operate the system at hand. In order to respond to this shortcoming, many international cooperation agencies and non-governmental organizations have prepared guidance documents for supporting authorities in the strategic planning process of waste management systems (e.g. (Wilson et al, 2001), (Kobus, 2003), (UNEP, 2009)).

In order to attain a successful implementation of waste management, the development of an integrated concept is necessary. This approach minimizes and can even eliminate counterproductive effects that result from the uncoordinated implementation of individual waste management measures. Through the development of a holistic and systemic concept, which harmonizes efforts to improve waste management, extra costs and unnecessary organizational effort are minimized, and the efficiency of the system is increased. Otherwise, if coordinated action is not considered beforehand, individual activities result in higher costs, consuming the already limited budget and constraining the implementation of additional, but necessary, measures.

In most cases where strategic planning is used, it is limited mainly to the definition of a baseline, setting of goals, and to derive some broad strategies based on the unquestioned assumption that they will help achieve the goal. Furthermore, there is little guarantee that the strategic decisions made will be successfully translated into operational rules so that the goals are achieved by the expected time, at an acceptable cost, and through a socially desirable process as the future plays out. An example is the strategic decision of defining a given percentage of biowaste diversion from landfilling in order to curb down the emission of greenhouse gases. The problem is that the current methods used in strategic planning in waste management do not enable to link the decisions with the way the system works in order to evaluate their impact on the goals. Moreover, in cases where strategic decisions have been made and have resulted in unfavorable outcomes, the current methods have little to offer when it comes to identifying the true root causes underlying the undesirable performance. The author believes that the pervasiveness of the waste management issues in urban centers seems to emerge from policies that are not cognizant of the dynamic complexity that arises from feedbacks, accumulations, time delays, and nonlinearities. Therefore, by using System Dynamics to test waste management policies, such as the ones developed for Addis Ababa, the shortcomings of traditional strategic planning can be overcome in the context of low and middle-income countries.

5. Model Conceptualization for Strategic Planning in Waste Management

The conceptualization of the model for sustainable waste and resource management has been structured around to the five basic functions that a waste management system can provide to society in order to transform an undesirable state into a desirable one. Based on Wilson's (2007) definition of development drivers for waste management, the five functions that have been identified are:

1. Public health protection
2. Value recovery
3. Pollution control
4. Resource conservation
5. Climate protection

Observation of the waste management situation different regions of the world (Scheinberg et al, 2010) indicate that, depending on the level of economic development and state of environmental regulation of a country, the focus may be towards the beginning or the end of the scale of system functions. For example, in low-income countries, the focus public sector may lie only on the protection of public health, while the informal sector is interested on the recovery of valuables from wastes. In middle-income countries, the focus currently is towards the formalization of value recovery chain and on the pollution control drivers, while high-income countries, which have already successfully transitioned through the three previous stages, are concentrating their efforts towards resource conservation and climate protection through sustainable waste management.

The fact that high-income countries have transitioned from an end of pipe policy mindset to an integrated resource management paradigm, while still being able to guarantee the protection of public health and value recovery, indicates that different driving forces do not act in isolation but interact constantly with each other. Figure 1 illustrates how the different system functions strengthen each other. For example, even though the response to environmental degradation is the control of pollution from dumpsites, capturing and flaring of landfill gas contributes to climate protection, while the treatment of leachate improves sanitation and public health conditions. Meanwhile, commodity scarcity leads to the recovery of value from waste materials, which in turn strengthens resource conservation and pollution control. Moreover, while rising natural resource consumption stimulates the conservation of resources, this strategy indirectly leads to public health protection, pollution control, and climate protection. Finally increase in greenhouse gas emissions enhances climate protection strategies, probably after a delay, which in turn influence how pollution control and resource conservation strategies are carried out.

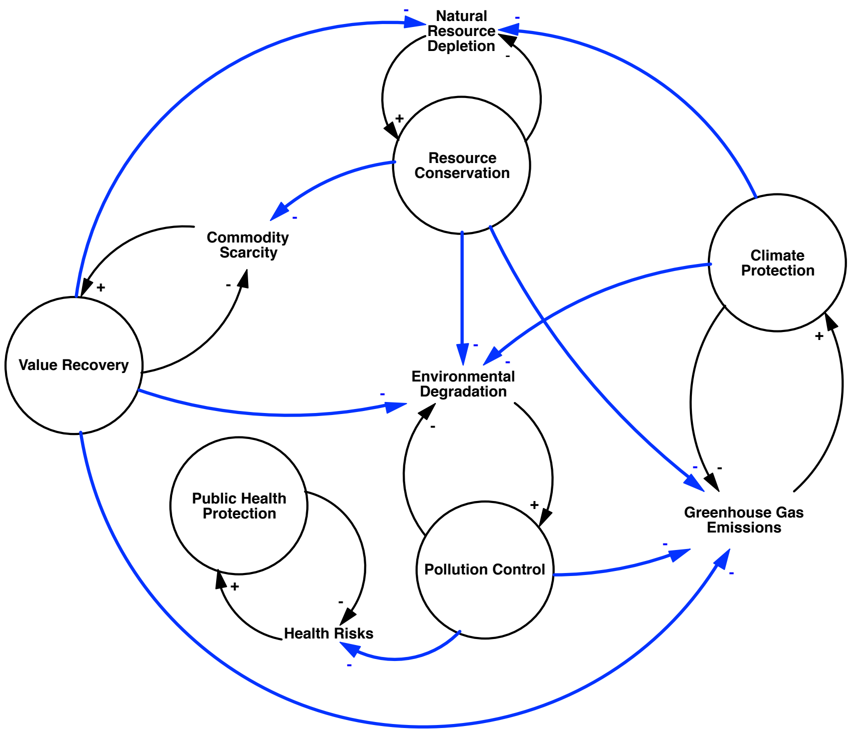

Figure 1 – Policy Drivers of Waste Management

6. Modeling for Capacity Planning

For the IGNIS project it is important to demonstrate that the technological concepts developed by the project have the potential of improving waste management in future megacities. This involves testing if when implemented in a city like Addis Ababa, these technological solutions can contribute to the alleviation of the current problematic situation. Additionally, it is important for the IGNIS project to find out to what extent could the performance (financial, socioeconomic, environmental, etc.) of the waste management system improve as a result from the implementation of the waste management strategies it proposed. This would be done by comparing the future development of the system in the absence of the strategies (business as usual) with the development of the system in the presence of the strategies.

The model that will be presented is just a concept model that should serve as a basis for discussion with stakeholders and decision makers at the outset of a participatory modeling process in order to show the difference between the base case and alternative management strategies. Figure 2 illustrates the overall model structure representing a simplified waste management system. A more detailed view of the model with corresponding equations can be found in the appendix.

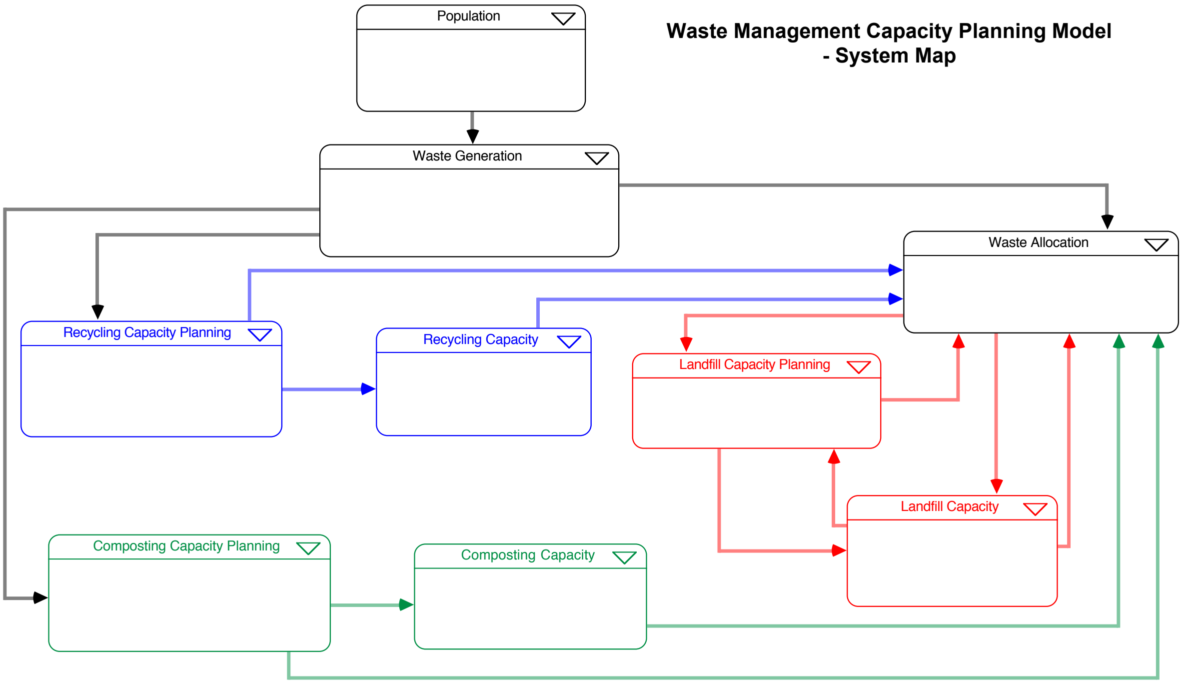

Figure 2 - Overall Model Structure

The model captures the basic physical components of an ideal waste management system such as waste generation, final disposal, and resource recovery, and is composed of nine sectors, which are interconnected. The population sector is the major driver of the system, as it is responsible for determining the amounts of waste generated. Figure 3 depicts the basic structure of the population sector, in which the number of people living in an area are increased by births and decreased by deaths[2]. Since population growth is an endogenous process, a fraction of the population reproduces leading to new births, while deaths are represented as the fraction of the population that leaves the population stock after they have reached the expected lifetime.

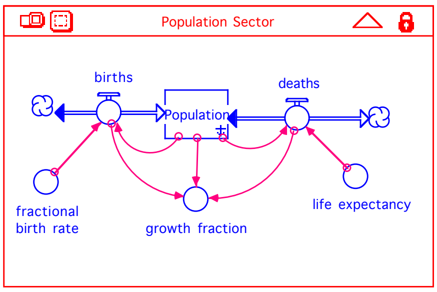

Figure 3 - Structure of Population Sector

Figure 4 shows the waste generation sector, which assumes that that three fractions of waste are generated, and that they are computed based on yearly

[2] Migration in and out of the area is left out in order to maintain the concept model as simple as possible. The model can be extended to incorporate these flows.

waste generation and the percentage of the total waste mass that each fraction. In this case values biowaste corresponds to 50% of the waste generated, recyclables to 25%, and residuals to the remaining 25%.

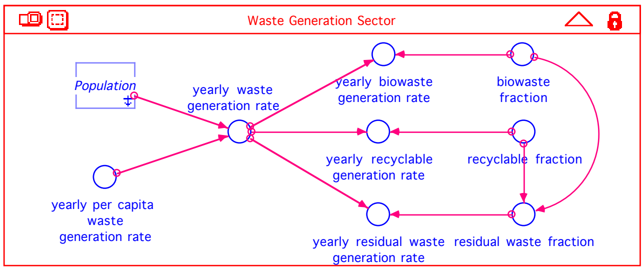

Figure 4 - Structure of Waste Generation Sector

Additionally, the based on the expected amount of biowaste and recyclables to be collected, the treatment capacity planning sectors emulates the decision process of forecasting the desired composting and recyclable capacity for a design horizon. Figure 5 shows the structure of the composting capacity planning sector as an example of how the planning process of treatement capacity takes place in the model. The difference between the desired capacity and the installed capacity is constructed over a period of time, and then put into operation (Figure 6). Therefore, the amount of biowaste and recyclables treated is determined either by the fraction of materials that can be collected (defined by a collection fraction) or by the available the treatment capacity, which ever is lowest. Biowaste and recyclables not treated end up commingled with residual waste will be disposed in a landfill. Alternatively, if there is lack of landfill capacity, then the residual waste will be disposed illegally (Figure 7). This allocation process assumes that as the capacity of the landfill decreases, the pressure towards illegal dumping rises. Such an assumption needs to be validated and tested during the modeling process with stakeholders, as it may vary under different social and economic contexts. In the end, the materials that have not been recovered, composted, incinerated, or illegally dumped will be disposed of at the sanitary landfill.

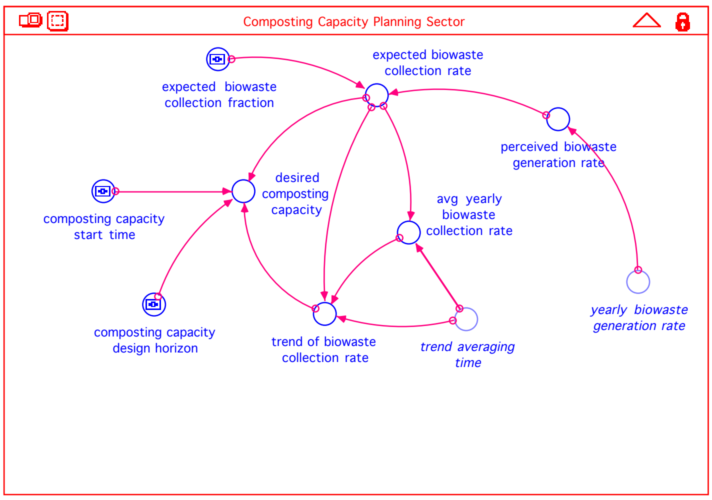

Figure 5 - Example of a Treatment Capacity Planning Sector

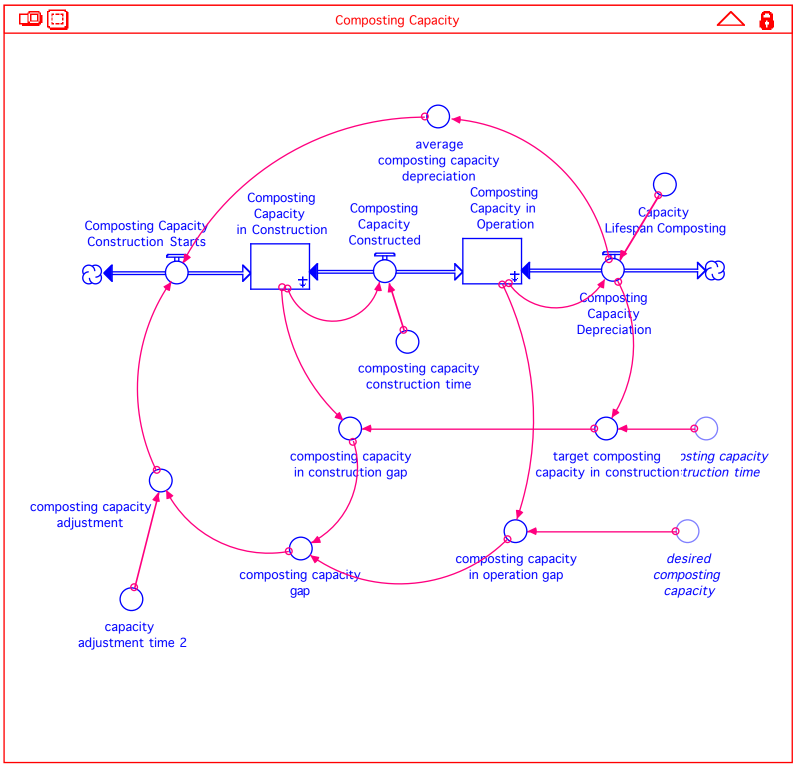

Figure 6 - Example of Treatment Capacity Sector

Figure 8 illustrates how the decision making process that determines the necessary landfill capacity is represented in the model, which has a different structure from that for the treatment facilities. It can be observed that the indicated landfill capacity to be developed depends on the perceived landfill capacity, as decision makers do not know the exact landfill capacity. Therefore, an information delay process is used to represent the fact that planners only observe the value of actual landfill capacity after a time lag. The model forecasts the waste disposal rate based on the historical development, and estimates the landfill capacity needed at the end of the planning horizon for the landfill (in this case 20 years). The model then compares the remaining landfill life with the planning horizon, and as the remaining landfill life decreases the pressure to develop a new landfill facility rises. Once the pressure is high enough a new landfill planning process is started, and after 10 years of development and construction, the additional landfill capacity is put into operation and the pressure to build new landfill capacity subsides.

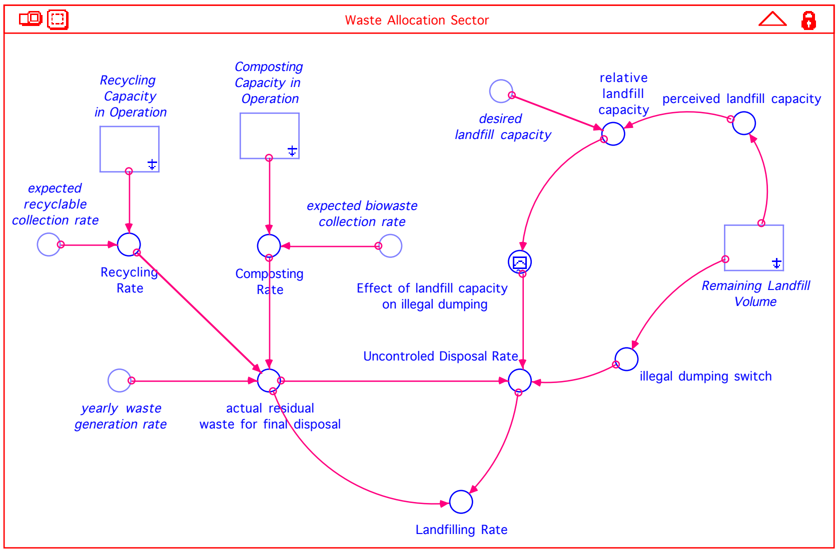

Figure 7 - Structure of Waste Allocation Sector

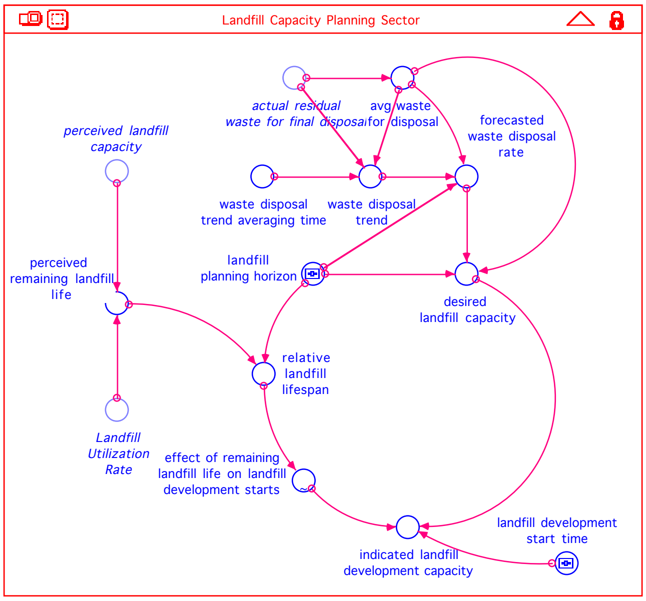

Figure 8 - Structure of Landfill Capacity Planning Sector

7. Scenario Simulations

The model will be now used to describe different scenarios regarding the strategic planning process in a fictitious urban area or region with 3 million inhabitants and a per capita waste generation of 1 kg/inh/day. As a baseline a system without any kind of waste management technology is simulated over a 100 year period to observe what is the long term behavior of the system. In order to understand better how the dynamics result from the model structure, the policy testing is carried out for zero population growth. Figure 9 shows that the model generates the expected behavior, as all waste goes to illegal dumping since there are no other treatment facilities.

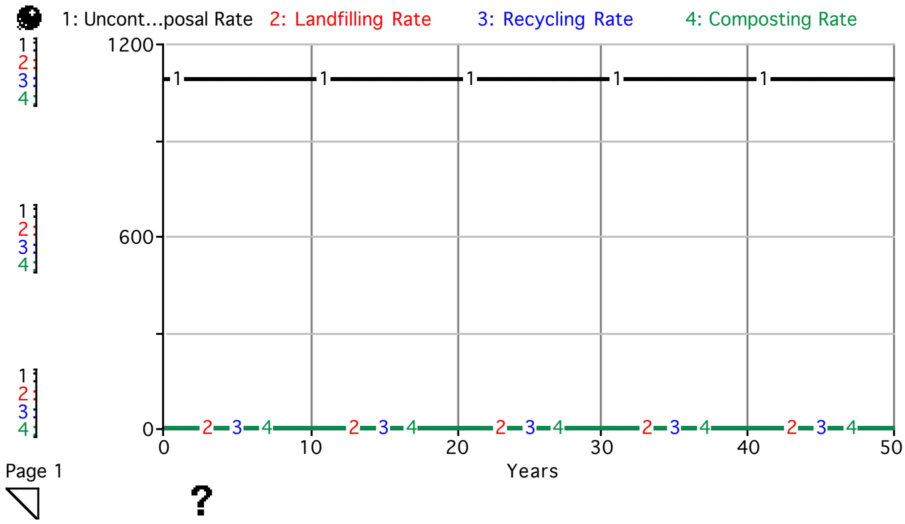

Figure 9 - Baseline Scenario

The second scenario analyzed is the introduction of a landfill development and construction process 5 years into the simulation. The design horizon is set at 30 years and the time to develop the disposal capacity is 10 years. Figure 10 shows that the landfill starts to operate 15 years after the simulation has started, and that from the beginning all of the waste is sent to the landfill.

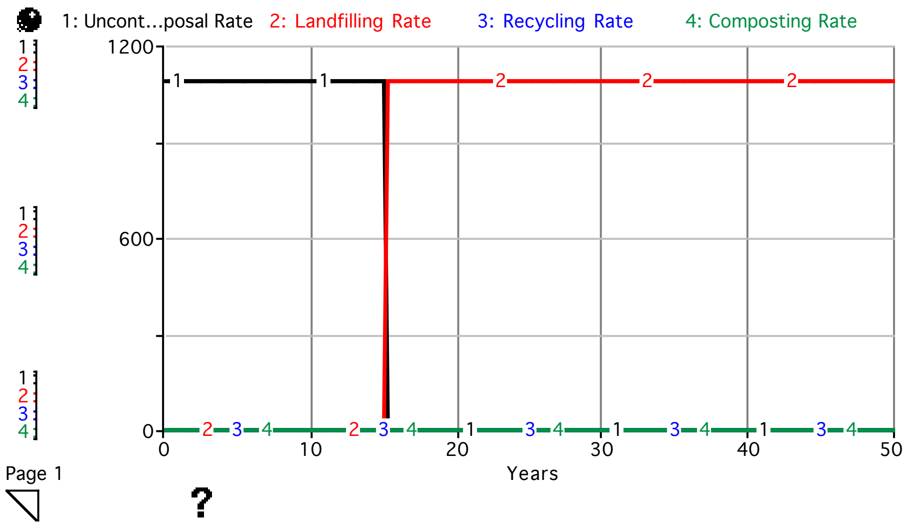

Figure 10 – Landfill Development Scenario

Figure 11 illustrate what would be the result, if after 10 years the municipality introduces starts to develop source separation and recovery of recyclables under the assumption that a 80% of the recyclable material generated can be recovered. Since it takes on average 5 years to bring the installed capacity into operation, which includes licensing, design, and construction, it takes more than a decade to achieve the desired recycling capacity. As a result of the diversion of recyclables to the the total amount of waste going to the landfill is lower.

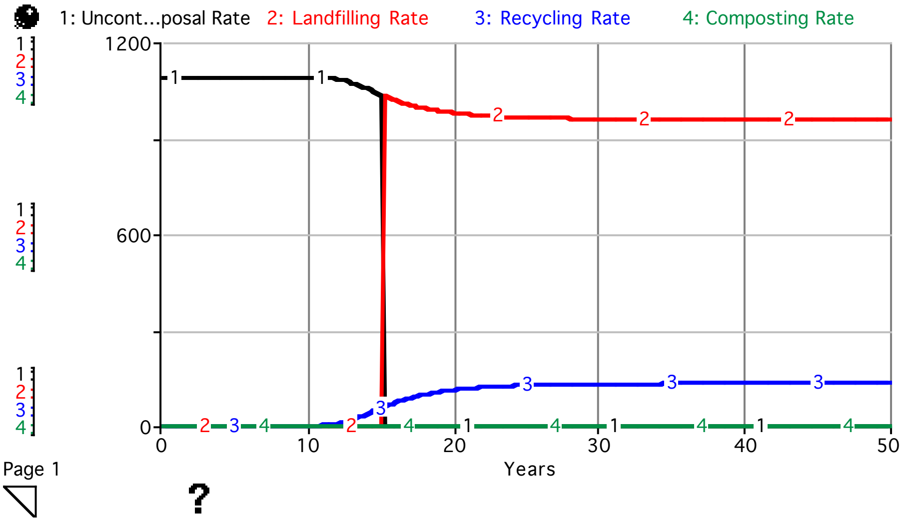

Figure 11 – Landfill and Recycling Development Scenario

The fourth scenario (Figure 12) simulated is the introduction of composting in the year 15 into the simulation. It is assumed that 70% of biowaste can be effectively collected and taken to the treatment facility. As biowaste is a large portion of the waste generated, the landfilling rate drops substantially.

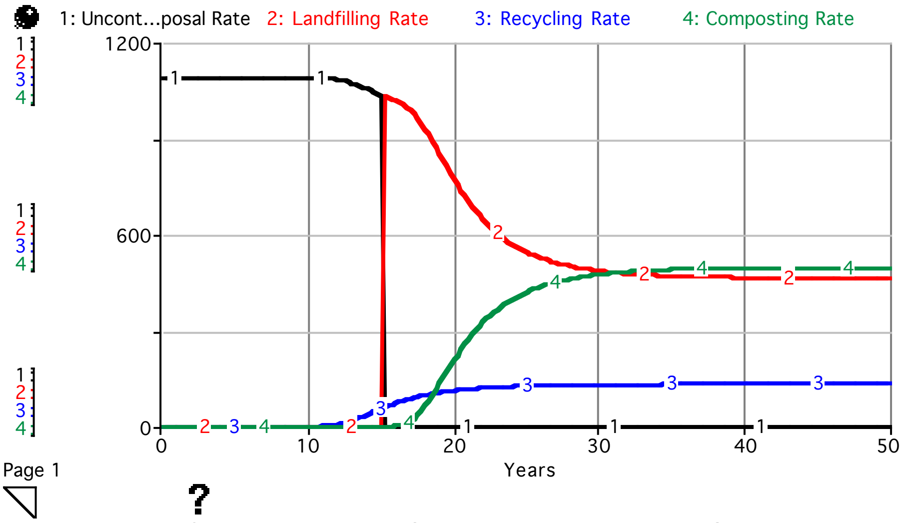

Figure 12 – Landfill, Recycling, and Composting Development Scenario

8. Outlook

Within the scope of the IGNIS project, two types of models will be constructed in order to allow for the comparison of the impact that the formulated strategies would have. At the core of this set of models is the “explanatory model”, which describes the current situation and serves as the basis for comparison for the evaluation of the alternative strategies. This explanatory model depicts the way waste management operations are currently configured, and how they interact to generate the current pattern of performance of waste management. The second type of models represents the design and implementation of alternative strategies for sustainable waste management. However, these “strategy testing models” do not work alone, but instead are built on top of the explanatory

model. Therefore, while the explanatory model describes the way the situation (e.g. financial, environmental, socioeconomic) could evolve given that the conditions remain the same as in the present, the strategy testing models show which changes would occur if the proposed strategies would be introduced.
Consequently, the explanatory model plays a very important role for identifying leverage points to improve the current performance and for the testing of the alternative waste management strategies. This means that the model needs to be a robust well-validated model, which can simulate the behavior of waste management system for the right causes. In order to achieve this, the current problematic situation and the decision processes that lead to it need to be captured accurately. This means that the model needs to represent with high fidelity how the managers and actors in the system make their decisions, which then lead to actions that change the state of the system. This level of fidelity can only be achieved when the managers and planners themselves express the way they make their decisions and are included in the model. This will lead later to a higher acceptance of the simulation results and strategy testing scenarios. As a result, a participatory modeling process is being structured to engage local authorities and stakeholders.

9. Conclusions

Instead of setting out to model a whole system, which would aim at forecasting, the modeling effort should focus on slicing the complex problem so that a policy intervention is viable. (Saeed, 1992). This means that the involvement of a problem owner or owners is a key issue. Therefore, the model that was presented is just a concept model that should serve as a basis for discussion with stakeholders and decision makers at the outset of a participatory modeling process in order to show the difference between the base case and alternative management strategies. Nonetheless, the model does help gain important insights regarding the qualitative improvement that could be obtained through the implementation of the explored strategies.

In order to obtain a reliable model for waste and resource management planning other aspects beyond the system's infrastructure capacity need to be considered. For example, financial, land, and human resources are allocated during the process of capacity expansion and upkeep, and as their availability drops, it constrains the expansion and growth of waste treatment capacity. This issue is not considered in this version of the model, not because it is not considered important, but because the decision rules that govern investment, land allocation, and staff hiring processes need to be elicited together with the people in the that make these decisions. Furthermore, the model does not represent a specific case of city, a region, or a country, but is a concept model of a class of systems that can be helpful for discussion potential strategies in the context of a model-based strategic planning process.

10. Acknowledgements

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APPENDIX – Model Equations

Composting Capacity Planning Sector
avg_yearly_biowaste_collection_rate =
SMTH1(expected_biowaste_collection_rate,trend_averaging_time)
Composting_Capacity_Design_Horizon = 10
Composting_Capacity_Start_Time = 15
desired_composting__capacity =
STEP((expected_biowaste_collection_rate*(1+Composting_Capacity_Design_Horizon*trend_of_biowaste_collection_rate)),Composting_Capacity_Start_Time)
expected_biowaste_collection_rate =
expected__Biowaste_Collection_Fraction*perceived_biowaste_generation_rate
expected__Biowaste_Collection_Fraction = .7
perceived_biowaste_generation_rate = SMTH1(yearly_biowaste_generation_rate,1)
trend_of_biowaste_collection_rate = IF avg_yearly_biowaste_collection_rate=0
THEN 0
ELSE (expected_biowaste_collection_rate-avg_yearly_biowaste_collection_rate)/(avg_yearly_biowaste_collection_rate*trend_averaging_time)

Composting Capacity
Composting_Capacity__in_Construction(t) = Composting_Capacity__in_Construction(t - dt) +
(Composting_Capacity_Construction_Starts - Composting_Capacity_Constructed) * dt
INIT Composting_Capacity__in_Construction = 0
INFLOWS:
Composting_Capacity_Construction_Starts =
average_composting_capacity_depreciation+composting_capacity_adjustment
OUTFLOWS:
Composting_Capacity_Constructed =
SMTH3(Composting_Capacity_Construction_Starts,composting_capacity_construction_time)
Composting__Capacity_in__Operation(t) = Composting__Capacity_in__Operation(t - dt) +
(Composting_Capacity_Constructed - Composting_Capacity_Depreciation) * dt
INIT Composting__Capacity_in__Operation = 0
INFLOWS:
Composting_Capacity_Constructed =
SMTH3(Composting_Capacity_Construction_Starts,composting_capacity_construction_time)
OUTFLOWS:
Composting_Capacity_Depreciation =
Composting__Capacity_in__Operation/Capacity__Lifespan_Composting
average_composting_capacity_depreciation = SMTH1(Composting_Capacity_Depreciation,1)
capacity__adjustment_time_2 = 1
Capacity__Lifespan_Composting = 20
composting_capacity_adjustment = composting_capacity_gap/capacity__adjustment_time_2
composting_capacity_construction_time = 5
composting_capacity_gap =
composting_capacity_in_construction_gap+composting_capacity_in_operation_gap
composting_capacity_in_construction_gap = target_composting_capacity_in_construction-Composting_Capacity__in_Construction
composting_capacity_in_operation_gap = desired_composting__capacity-Composting__Capacity_in__Operation
target_composting_capacity_in_construction =
Composting_Capacity_Depreciation*composting_capacity_construction_time

Landfill Capacity Planning Sector
avg_waste__for_disposal = SMTH1(actual_residual_waste_for_final_disposal,5)
desired__landfill_capacity =
(avg_waste__for_disposal+forecasted_waste_disposal_rate)*Landfill_Planning_Horizon/2

forecasted_waste_disposal_rate =
avg_waste__for_disposal*(1+Landfill_Planning_Horizon*waste_disposal_trend)
indicated_landfill_development_capacity = IF TIME<Landfill_Development_Start_Time

THEN 0

ELSE
desired__landfill_capacity*effect_of_remaining_landfill_life_on_landfill_development_starts
Landfill_Development_Start_Time = 5
Landfill_Planning_Horizon = 30
perceived_remaining_landfill_life = SMTH1(remaining_landfill_lifetime,2)
relative_landfill_lifespan = perceived_remaining_landfill_life/Landfill_Planning_Horizon
waste_disposal_trend = IF avg_waste__for_disposal = 0
THEN 0
ELSE (Max((actual_residual_waste_for_final_disposal-
avg_waste__for_disposal)/(avg_waste__for_disposal*waste_disposal_trend_averaging_time),0)
)
waste_disposal_trend_averaging_time = 2
effect_of_remaining_landfill_life_on_landfill_development_starts =
GRAPH(relative_landfill_lifespan)
(0.00, 1.00), (0.1, 0.95), (0.2, 0.75), (0.3, 0.3), (0.4, 0.15), (0.5, 0.05), (0.6, 0.00), (0.7, 0.00),
(0.8, 0.00), (0.9, 0.00), (1, 0.00)

Landfill Capacity
Landfill_Capacity_in_Construction(t) = Landfill_Capacity_in_Construction(t - dt) +
(Landfill__Construction_Starts - Landfill_Construction_Finishing) * dt
INIT Landfill_Capacity_in_Construction = 0
    TRANSIT TIME = varies
    INFLOW LIMIT = ∞
    CAPACITY = ∞
INFLOWS:
Landfill__Construction_Starts = landfill_capacity_adjustment
OUTFLOWS:
Landfill_Construction_Finishing = CONVEYOR OUTFLOW
    TRANSIT TIME = landfill_construction_time
Remaining_Landfill_Volume(t) = Remaining_Landfill_Volume(t - dt) +
(Landfill_Construction_Finishing - Landfill_Utilization_Rate) * dt
INIT Remaining_Landfill_Volume = 0
INFLOWS:
Landfill_Construction_Finishing = CONVEYOR OUTFLOW
    TRANSIT TIME = landfill_construction_time
OUTFLOWS:
Landfill_Utilization_Rate = MIN(Landfilling_Rate,Remaining_Landfill_Volume)
Utilized_Landfill__Capacity(t) = Utilized_Landfill__Capacity(t - dt) + (Landfill_Utilization_Rate) *
dt
INIT Utilized_Landfill__Capacity = 0
INFLOWS:
Landfill_Utilization_Rate = MIN(Landfilling_Rate,Remaining_Landfill_Volume)
avg_landfill_utilization_rate = SMTH1(Landfill_Utilization_Rate,10)
landfill_capacity_adjustment = landfill_capacity_gap/time_to_adjust_capacity
landfill_capacity_gap = indicated_landfill_development_capacity-
(Landfill_Capacity_in_Construction+Remaining_Landfill_Volume)
landfill_construction_time = 10
remaining_landfill_lifetime = IF Landfill_Utilization_Rate=0 THEN 0 ELSE
Remaining_Landfill_Volume/Landfill_Utilization_Rate
time_to_adjust_capacity = 1

Population Sector
Population(t) = Population(t - dt) + (births - deaths) * dt
INIT Population = 3
INFLOWS:
births = Population*fractional_birth_rate
OUTFLOWS:
deaths = Population/life_expectancy
fractional_birth_rate = 0.02
growth_fraction = (births-deaths)/Population
life_expectancy = 50

Recycling Capacity
Recycing__Capacity__in_Construction(t) = Recycing__Capacity__in_Construction(t - dt) + (Recycling__Capacity_Construction_Starts - Recycling_Capacity_Constructed) * dt
INIT Recycing__Capacity__in_Construction = 0
INFLOWS:
Recycling__Capacity_Construction_Starts =
average_recycling_capacity_depreciation+recycling_capacity_adjustment
OUTFLOWS:
Recycling_Capacity_Constructed =
SMTH3(Recycling__Capacity_Construction_Starts,recycling_capacity_construction_time)
Recycling__Capacity_in_Operation(t) = Recycling__Capacity_in_Operation(t - dt) + (Recycling_Capacity_Constructed - Recycling_Capacity_Depreciation) * dt
INIT Recycling__Capacity_in_Operation = 0
INFLOWS:
Recycling_Capacity_Constructed =
SMTH3(Recycling__Capacity_Construction_Starts,recycling_capacity_construction_time)
OUTFLOWS:
Recycling_Capacity_Depreciation =
Recycling__Capacity_in_Operation/Capacity__Lifespan_Recycling
average_recycling_capacity_depreciation = SMTH1(Recycling_Capacity_Depreciation,1)
capacity__adjustment_time = 1
Capacity__Lifespan_Recycling = 20
recycling_capacity_adjustment = recycling_capacity_gap/capacity__adjustment_time
recycling_capacity_construction_time = 5
recycling_capacity_gap =
recycling_capacity_in_construction_gap+recycling_capacity_in_operation_gap
recycling_capacity_in_construction_gap = target_recycling_capacity_in_construction-Recycing__Capacity__in_Construction
recycling_capacity_in_operation_gap = desired_recycling__capacity-Recycling__Capacity_in_Operation
target_recycling_capacity_in_construction =
Recycling_Capacity_Depreciation*recycling_capacity_construction_time

Recycling Capacity Planning Sector
avg_yearly_recyclable_collection_rate =
SMTH1(expected_recyclable_collection_rate,trend_averaging_time)
desired_recycling__capacity =
STEP((expected_recyclable_collection_rate*(1+Recycling_Capacity_Design_Horizon*trend_of_recyclable_collection_rate)),Recycling_Capacity_Start_Time)
Expected_Recyclable_Collection_Fraction = .8
expected_recyclable_collection_rate =
Expected_Recyclable_Collection_Fraction*perceived_recyclable_generation_rate
perceived_recyclable_generation_rate = SMTH1(yearly_recyclable_generation_rate,1)
Recycling_Capacity_Design_Horizon = 10
Recycling_Capacity_Start_Time = 10
trend_averaging_time = 1
trend_of_recyclable_collection_rate = IF avg_yearly_recyclable_collection_rate = 0

THEN 0
ELSE (expected_recyclable_collection_rate-avg_yearly_recyclable_collection_rate)/(avg_yearly_recyclable_collection_rate*trend_averaging_time)

Waste Generation Sector
Biowaste_Fraction = .65
Recyclable_Fraction = .15
residual_waste_fraction = 1-Biowaste_Fraction-Recyclable_Fraction
yearly_biowaste_generation_rate = Biowaste_Fraction*yearly_waste_generation_rate
yearly_per_capita__waste_generation_rate = 365 {kg/inh/year}
yearly_recyclable_generation_rate = Recyclable_Fraction*yearly_waste_generation_rate
yearly_residual_waste_generation_rate = residual_waste_fraction*yearly_waste_generation_rate
yearly_waste_generation_rate = Population*yearly_per_capita__waste_generation_rate

Waste Allocation Sector
actual_residual_waste_for_final_disposal = yearly_waste_generation_rate-Recycling_Rate-Composting_Rate
Composting_Rate = MIN(Composting__Capacity_in__Operation,expected_biowaste_collection_rate)
illegal_dumping_switch = IF Remaining_Landfill_Volume>0 THEN 0 ELSE 1
Landfilling_Rate = actual_residual_waste_for_final_disposal-Uncontroled_Disposal_Rate
perceived_landfill_capacity = SMTH1(Remaining_Landfill_Volume,2)
Recycling_Rate = MIN(Recycling__Capacity_in_Operation,expected_recyclable_collection_rate)
relative_landfill_capacity = IF perceived_landfill_capacity= 0 THEN 0 ELSE perceived_landfill_capacity/desired__landfill_capacity
Uncontroled_Disposal_Rate = actual_residual_waste_for_final_disposal*(0*Effect_of_landfill_capacity_on_illegal_dumping+1*illegal_dumping_switch)
Effect_of_landfill_capacity_on_illegal_dumping = GRAPH(relative_landfill_capacity)
(0.00, 1.00), (0.1, 0.2), (0.2, 0.1), (0.3, 0.05), (0.4, 0.025), (0.5, 0.00), (0.6, 0.00), (0.7, 0.00), (0.8, 0.00), (0.9, 0.00), (1, 0.00)