A System Dynamics Model for Cost-Benefit Analysis of Stray Dog Population Management

An Interactive Qualified Project Report

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by

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Report submitted to:

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Abstract

Free-ranging dogs (FRD) represent around three-fourths of the world's dog population and are essentially generations of abandoned pets that survive on human-derived materials and wildlife. Due to their increasing populations, many countries have experimented with various policies to reduce their population growth; however, most have failed due to unintended consequences and a serious lack of scientifically informed planning. This project uses Indian FRD as a case study to provide a new solution to this problem, taking into consideration FRD population dynamics, funding avenues, and innovative strategies to maintain FRD welfare and provide societal benefits at the same time. This project also produces a comprehensive model that features a wide range of factors imperative to planning a successful FRD population intervention. The goal, through the gaming environment, is that anyone from any nation experiencing an FRD problem can experiment with it to plan an effective intervention. The user can simulate cost-benefit analyses of all previously proposed interventions for FRD with the use of in-built parameters and inputs specific to the location involved. At the same time, the user will be able to simulate the benefits of using those same resources for a social integration effort, and thereby compare the outcomes and combinations of efforts. Structured as a generic global simulation, the parameters have been chosen such that relevant quantifiable factors for all regions and scenarios, such as population size, funding/resources, and FRD training time, can be considered carefully before planning any widescale effort.

Table of Contents

Table of Figures

Introduction and Problem Description

There are an estimated 750 million free-ranging dogs (FRD) in the world, representing approximately 70- 80% of the global dog population (Daniels 1989, Paul 2018, Hiby et al 2017). Depending on country and location, FRD can include a variety of stray purebreds, mixed-breed dogs, or dogs of specific landraces that have never been bred for domestication purposes. About 30-60 million FRD currently exist throughout urban and rural India, as a result of ineffective population interventions, weak pet control policies, and vast amounts of human-derived materials available for FRD survival (Ghosh 2018, Daniels 1989). With a human population of 1.6 billion and density up to around 21,000 people per square kilometer, India presents a complex situation for FRD-human interactions and annually reports one-third of global deaths from endemic canine rabies. Although FRD provide benefits of companionship and security as territorial, human commensals, they complicate rural/urban environments as disease transmitters and experience a high level of human-induced mortality and welfare problems such as diseases/infections, malnutrition, starvation, and injury or debilitating conditions (Rinzin 2015). FRD also globally pose a conservation threat for wildlife by transmitting zoonotic diseases, competing for resources, threatening as predators, and attacking a variety of species residing within protected areas (Rinzin 2015, Ghosh 2018, Home 2018). Since the recognition of welfare rights for stray animals from the late 20th century, several attempts have been made without success to manage this growing population in India and various other countries. The problem is common to almost every nation still today.

This IQP report will provide an overview of relevant literature and alternative hypotheses for the problem described above, followed by methodology used to develop the system dynamics model. This document will then describe the model I have constructed, followed by a series of experiments to assess the model's performance when applied to the problem at hand. Policy recommendations, areas for design improvement, and future directions will then be discussed, followed by overall conclusions for how this report adds to the body of existing knowledge. All model equations are provided in the Appendix of this report.

Alternative Hypotheses and Literature Review

Several population management interventions have been carried out in various countries over the years with notable reasons for failure. For example, an Animal Birth Control program in Bhutan aimed to control rabies failed due to poor funding, lack of public interest, and a low rate of overall sterilization (Rinzin 2015). General Srimoung of Thailand began a castration and adoption program for FRD in Bangkok, which eventually failed since a reduction in the number of dogs led to an increase in "immigrant" dogs taking advantage of the available niches in Bangkok, an entirely unintended consequence (Saeed 2009). The 2004 WHO Expert Committee stated that maintaining a stable FRD population would require 70% vaccination and 70% sterilization annually, which is impossible in most nations due to immense FRD populations and insufficient funding (Rinzin 2015).

The Comfort Dog Project by The BIG FIX Uganda is an exemplary case study due to their extensive, successful efforts in socially integrating Ugandan stray dogs in the later years of the Ugandan civil war (1980's to present) (Comfort Dog Project). Ugandan FRD were trained for an Animal-Assisted Intervention (AAI) to help civil war survivors with "psycho-social rehabilitation" through Human-Animal Interaction (HAI). This program has drastically reduced PTSD symptoms and lowered the regional suicide and substance use rate, through simple training measures. Despite numerous studies focusing on a variety of population interventions including sterilization programs, vaccination programs, culling measures, and policy measures for better pet control, no study has yet proven that this large and rapidly growing population can be effectively controlled using these commonly proposed measures.

Several underlying assumptions in this model are based on a generic stray dogs system dynamics model presented in Saeed (2009), based on Thailand's stray dog problem in the 1980's. The model, comprised of two interconnected sectors, is shown below.

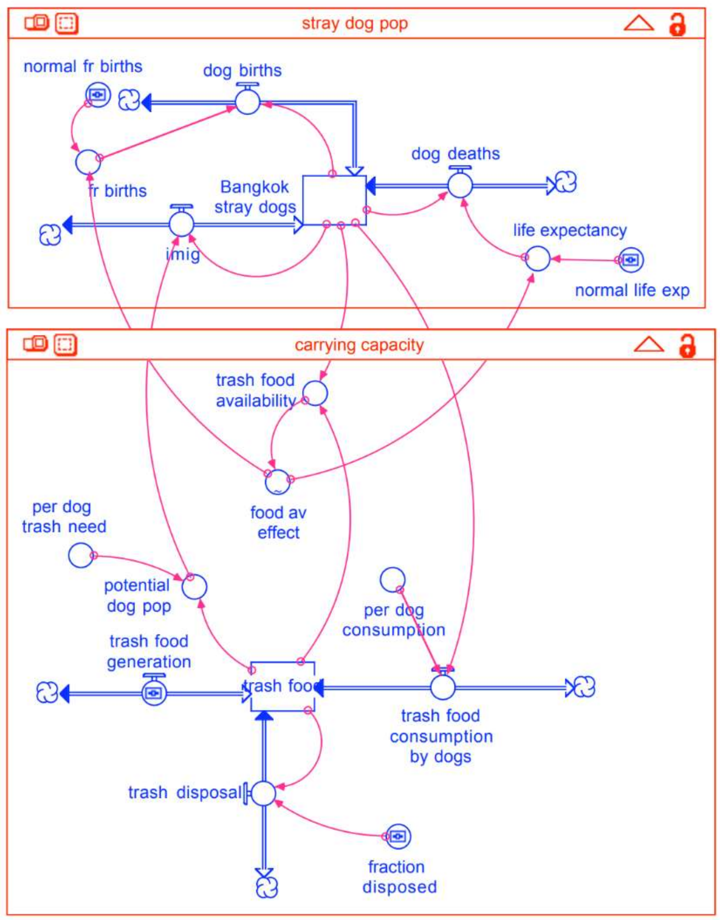


Figure 1. Stray dogs model from Saeed (2009).

This model, defining "Strays dogs as a manifestation of a latest capacity support system", creates a basic model for "pest populations" such as FRD that subsist largely on human-derived materials or waste. The first sector, "stray dog pop", includes the FRD population structure that has been introduced into this report's model. The castration and euthanasia policies can be implemented into this model by reducing and increasing the birth and death rates, respectively. The second sector, "carrying capacity", highlights trash food as the "latent capacity support structure" for FRD, which affects their birth rates and life expectancy depending on food availability. Four policies were simulated and discussed in the article, as shown below:

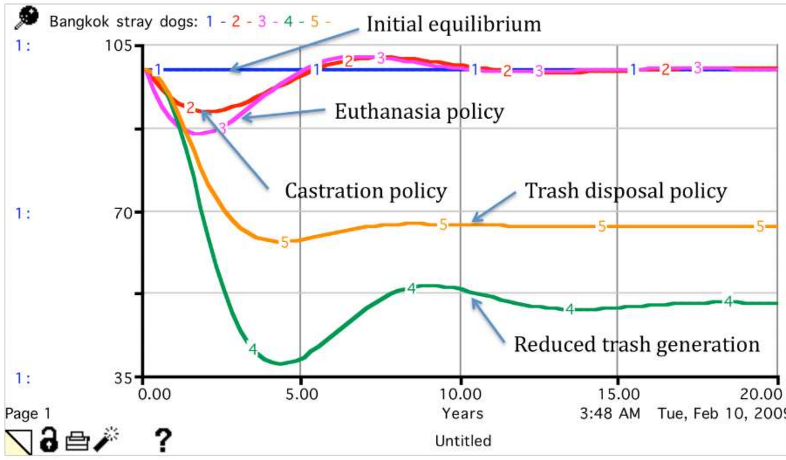


Figure 2. "Pest population response to various policy interventions" (Figure 3; Saeed, 2009).

The baseline Bangkok stray dog population is easily disturbed by the euthanasia and castration policies; however, it very quickly rebounds to an even higher population size before finding the baseline equilibrium again. The trash disposal policy has a better effect because it removes the support structure itself and reduces the food average effect on the FRD birth rate and life expectancy. Thus, the rebound is less, and the resulting equilibrium is significantly lower. The reduced trash generation policy proves to be the most effective because it decreases the inflow of trash food, thus weakening the support structure much earlier than disposing trash later on. The resulting equilibrium here is even lower and can be managed more efficiently than with a castration/euthanasia policy. Keeping the key lessons from this Thai FRD model in mind, the following model has been created for the Indian FRD context.

Objective

This model intends to inform students, policymakers, and the general public regarding the FRD problem plaguing many nations today and how various policies can be effectively combined to reduce the population with societal and welfare benefits over time.

Boundary

This model focuses on visualizing the effects of implementing four major population management policies on a user-defined FRD population. The model does not address corruption in funding and policy administration, although these are notable flaws that can reverse or negate any policy actions undertaken. Most importantly, although effects on wildlife conservation and public health have been thoroughly investigated, this model does not include these aspects of the FRD problem due to two main reasons. First, in several developing nations such as India, there is currently no database or extensive literature on exactly where and to what extent FRD cause livestock and wildlife depredation. Second, although effects of implementing social integration can increase public interest, animal welfare and service laws, and thereby funding, these remain qualitative in comparison to the rest of this model.

Methodology

This study took an entirely new and unexplored perspective towards the FRD problem and attempted to propose a novel solution. The integral challenge that this study addressed is that all population interventions in India have essentially failed from a lack of resources stemming from poor funding, corruption, and weak policies. This project features a STELLA model developed using system dynamics, as well as a gaming environment, that demonstrates a pathway for FRD assessment, training, and deployment into four main areas of public service: companion/pet, therapy, medical services, and specialized training fields such as law enforcement, military assistance, ecological data collection, and anti-poaching conservation efforts. By creating appropriate and necessary parameters for funding, societal costs and benefits, and laws, the model compares the costs and benefits of implementing previously proposed FRD interventions versus combined policies including social integration for public health and conservation benefits. Relevant statistical data from various sources, experiential data, and ecological relationships were also used to structure the model baseline and comparisons. The model focuses on India as a primary case study for data and information. Since the model requires parameter inputs that can be measured or deduced from historical data, the challenge remains that certain types of data from India and many other nations are absent or inaccurate.

Model Description

This section will first begin with an explanation of the feedback loops existing at the top-layer of the model. A detailed discussion of each module and the relationships of variables within it will follow.

I. Feedback loops at the top-layer

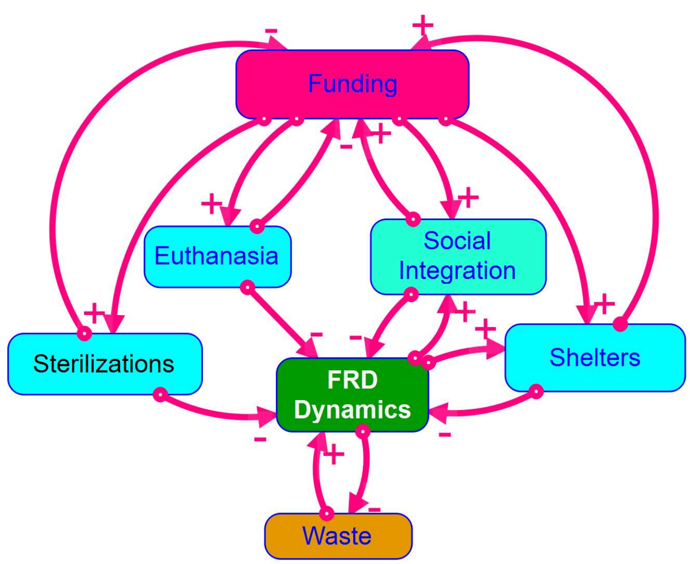


Figure 3. Links at the top-layer of the model.

The model shown above consists of seven modules, color-coded according to their functional roles, with positive and negative feedback links according to their internal structures. The module in green, *FRD Dynamics,* consists of the FRD population structure and points of policy implementation. The module in pink, *Fundin*g, consists of the budget, user-defined allocations, and methods of income. The modules in blue, *Sterilizations*, *Euthanasia*, and *Shelters*, each define a different policy that exists for FRD population management, while the green-blue module *Social Integration* consists of the proposed method of FRD management. The orange module, *Waste*, has been largely derived from the "carrying capacity" sector of "Stray dogs, street gangs and terrorists: manifestations of a latent capacity support system" (Saeed, 2009).

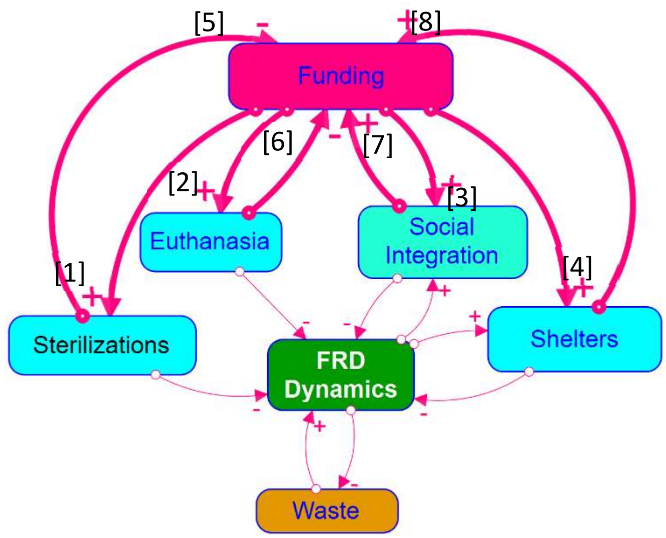


Figure 3.1 Feedback loops of *Funding* and the four policy modules.

The figure above highlights the four feedback loops between *Funding* and the four policies: *Sterilizations*, *Euthanasia*, *Social Integration*, and *Shelters*. For all policies, there is a positive direct link ([1] – [4]) between *Funding* and the policy, since increasing the budget creates more potential for budget allocations to these policies. For each of the conventional, previously-proposed policies, there is a negative direct link ([5],[6]) from the policy to the *Funding* module, whereas the *Social Integration* and *Shelters* policies have positive direct links ([7],[8]) to *Funding*, since they provide revenue streams.

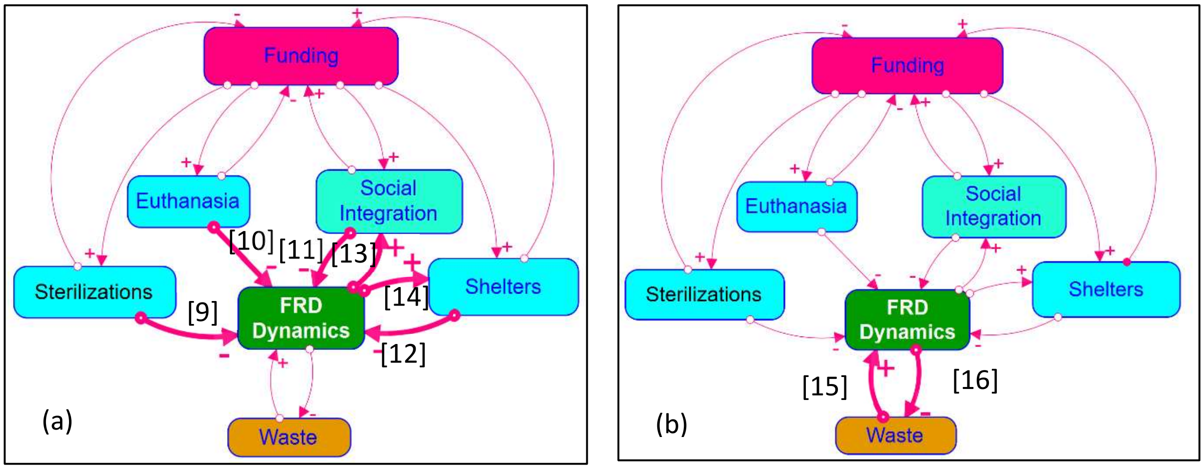


Figure 3.2 Feedback loops of *FRD Dynamics* and the (a) four policy and (b) *Waste* modules.

As seen in Figure 3.2a above, all of the four policies have negative direct links ([9],[10],[11],[12]) to *FRD Dynamics*, while there are positive direct links ([13],[14]) from *FRD Dynamics* back to the *Social Integration* and *Shelters* policies. As for Figure 3.2b, the *Waste* module positively links ([15]) to *FRD Dynamics*, while *FRD Dynamics* links negatively ([16]) to *Waste.* The effects of implementing the four policies is consistently negative on *FRD Dynamics* since the policies are intended to reduce the *FRD Population* stock, while greater *FRD Population* provides greater potential for both the *Social Integration* and *Shelters* policies since they benefit directly from the number of FRD that are available.

II. FRD Dynamics Module

The FRD population structure is shown in this module, in which all polices are implemented. The module figure is shown below.

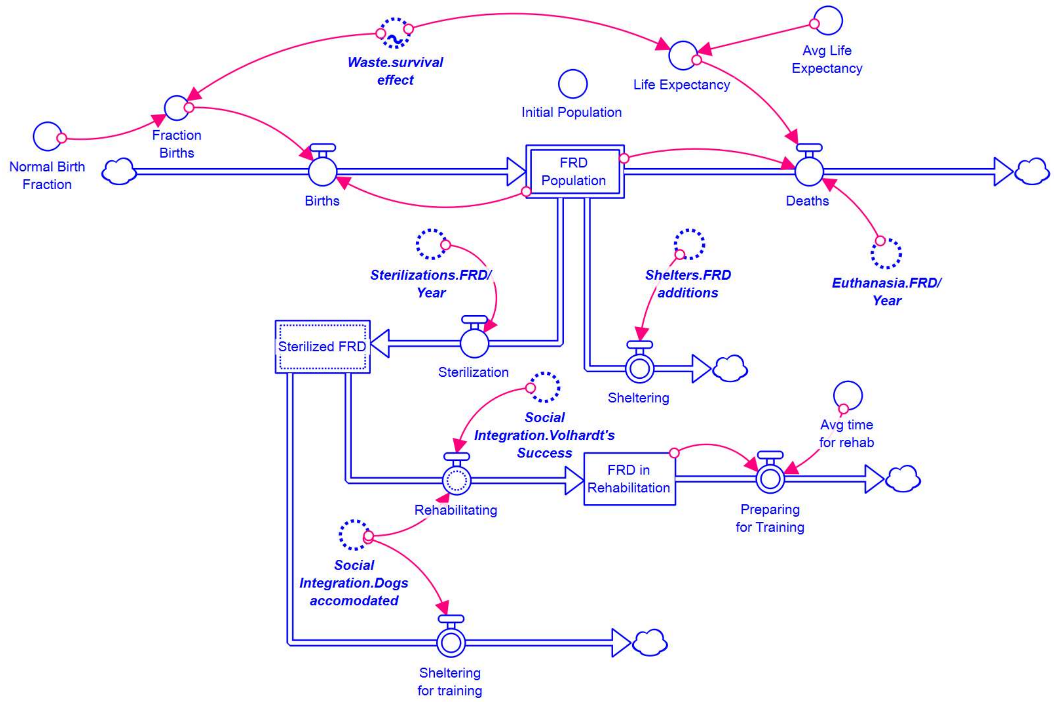


Figure 4. *FRD Dynamics* module.

The upper stock and flow region of this module depicts the FRD population dynamics structure consisting of an *FRD Population* stock, initialized using *Initial Population*, an inflow of *Births,* and an outflow of *Deaths.* As food availability is known to affect breeding rate and pup/adult survival, *Survival Effect* is shown here as a converter from the *Waste* module factoring into *Fraction Births* and *Life Expectancy* by multiplying with *Normal Birth Fraction* and *Avg Life Expectancy,* respectively. In the *Deaths* outflow of this population structure, *FRD/Year* from the *Euthanasia* policy module is inserted to add to the rate of FRD deaths.

The *Sterilization* outflow uses *FRD/Year* from the *Sterilizations* policy module to create a flow of FRD that are sterilized and accumulate them into the *Sterilized FRD* stock. From here, FRD will either flow through *Sheltering for training* or *Rehabilitating* when the *Social Integration* policy is activated. The main *Sheltering for training* flow uses the number of *Dogs accommodated* obtained from the policy module to place FRD into training for various streams. On the other hand, it can be expected that many FRD will initially fail the Volhardt's tests that tests dog disposition, calm behavior, and ability to undergo training, and will therefore enter the *Rehabilitating* flow based on *Volhardt's Success.* These rehabilitating FRD will not be in a shelter system, as it has been shown that shelters do not provide constructive spaces for dogs to recover from the aggressive or fearful behavior they attain while experiencing abuse and competition on the streets. Instead, they will be nurtured in calm, controlled environments for an *Average time for rehab,* which will allow them to exit the *FRD in Rehabilitation* stock by *Preparing for Training.* The third outflow from *FRD Population, Sheltering*, is determined by the number of *FRD additions* from the *Shelters* policy module. This converter defines the number of FRD that can be realistically housed in the shelter system per year, given available infrastructure.

The equations of stocks and flows are listed below:

FRD Population = ∫(Births - Deaths - Sterilization - Sheltering)dt
*Births = FRD Population*Fraction Births*
Deaths = FRD Population/Life Expectancy + Euthanasia.FRD/Year
Sterilization = Sterilizations.FRD/Year
Sheltering = Shelters.FRD additions
Sterilized FRD = ∫(Sterilization – Sheltering for training - Rehabilitating)dt
Sheltering for training = Social Integration.Dogs accommodated
*Rehabilitating = Social Integration.Dogs accommodated * (1 – Social Integration.Volhardt's Success)*
FRD in Rehabilitation = ∫(Rehabilitating – Preparing for Training)dt
Preparing for Training = FRD in Rehabilitation/Avg time for rehab
Avg Life Expectancy = 5
Avg time for rehab = 0.5
*Fraction Births = Normal Birth Fraction * Waste.survival effect*
Initial Population = 1000000
*Life Expectancy = Avg Life Expectancy * Waste.survival effect*
Normal Birth Fraction = 0.2

III. Waste Module

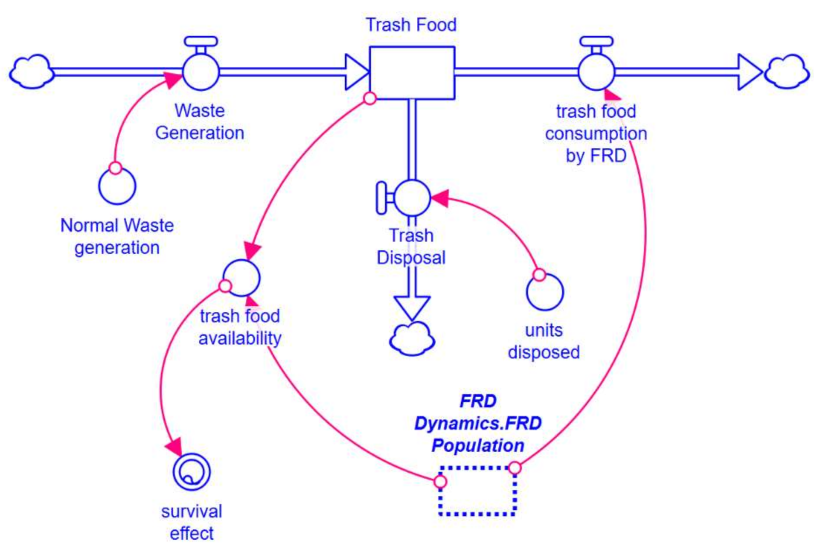


Figure 5. *Waste* module.

The carrying capacity sector of Saeed (2009) shown above has a major stock-flow structure of *Trash Food,* with an inflow of *Waste Generation,* determined by *Normal Waste generation* as defined by the user, and primary outflow of *trash food consumption by FRD*, which depends on the *FRD Population* from the *FRD Dynamics* module. The secondary outflow in this module, *Trash Disposal,* functions if *units disposed* is defined by the user. The *trash food* *availability* converter allocates food resource available per FRD by assigning each FRD one unit of "trash food" and this determines the *survival effect* graphical converter that affects FRD birth rate and life expectancy, as shown below.

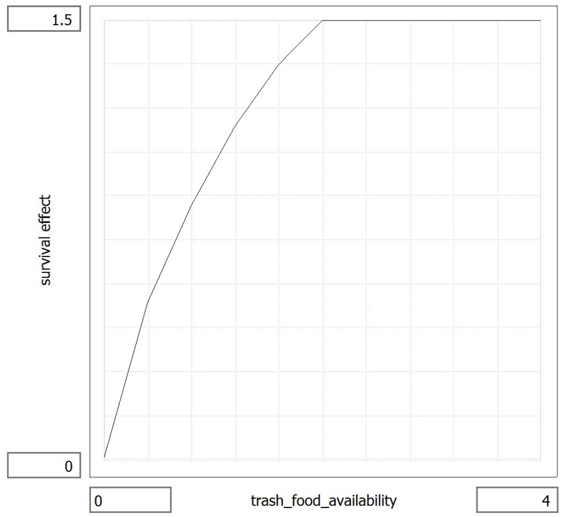


Figure 6. Effect of *trash food availability* on *survival effect.*

Survival effect increases from 0 to 1.5 depending on *trash food availability* and has a decreasing slope. The survival effect remains at 1.5 beyond *trash food availability* of 2, since there is a realistic limit on birth rate and life expectancy, especially for stray animals.

The equations for stocks, flows, and converters in this module are given below:

Trash Food = ∫(Waste Generation – trash food consumption by FRD – Trash Disposal)dt
Waste Generation = Normal waste generation
Trash food consumption by FRD = FRD Dynamics.FRD Population
Trash Disposal = units disposed
Normal Waste generation = 1000000
Trash food availability = Trash Food / FRD Dynamics.FRD Population
Units disposed = 0

IV. Sterilizations Module

The first policy described here remains the most popular method for FRD population management worldwide. Although Saeed (2009) showed this policy through a reduction in FRD birth rate, here it is being implemented as a policy causing outflow of FRD from the stock population, into a new stock of sterilized FRD who can be trained and adopted.

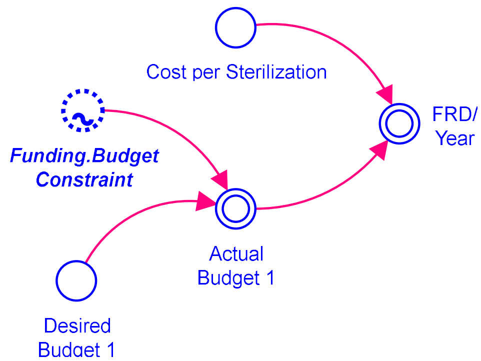


Figure 7. *Sterilizations* module.

The module shown above provides the user with inputs for the sterilization policy. Once the user defines the *Desired Budget 1*, the *Budget Constraint* from the *Funding* module factors into the *Actual Budget 1* for sterilization. Dividing the final budget by the user-defined *Cost per Sterilization* for each FRD gives the *FRD/Year* that can be sterilized.

The equations for converters in this module are given below:

*Actual Budget 1 = Desired Budget 1 * Funding.Budget Constraint*
Cost per Sterilization = 1000
Desired Budget 1 = 0
FRD/Year = Actual Budget 1 / Cost per Sterilization

V. Euthanasia Module

The euthanasia policy in this model causes the FRD death rate to increase and can also be used to visualize the effects of culling policies, which have been used in many countries including Canada, India, Indonesia, Mexico, and Romania. It is widely criticized as a harmful policy for animal welfare as well as human mental health, and many efforts have been made to stop this policy from being implemented.

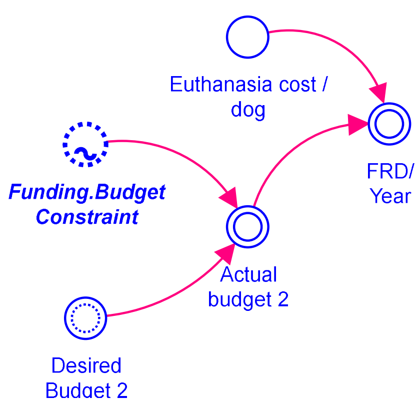


Figure 8. *Euthanasia* module.

This module, similar to the *Sterilizations* module above, provides the basis for the euthanasia policy on FRD population management. The user-defined *Desired Budget 2,* multiplied by the *Budget Constraint* determines the *Actual Budget 2* available for euthanasia. This budget, divided by the user-defined *Euthanasia cost/dog,* gives the *FRD/Year* that can be put down.

The equations for converters in this module are given below:

*Actual budget 2 = Desired Budget 2 * Funding.Budget Constraint*
Desired Budget 2 = 0
Euthanasia cost/dog = 1000
FRD/Year = Actual budget 2 / Euthanasia cost/dog

VI. Shelters Module

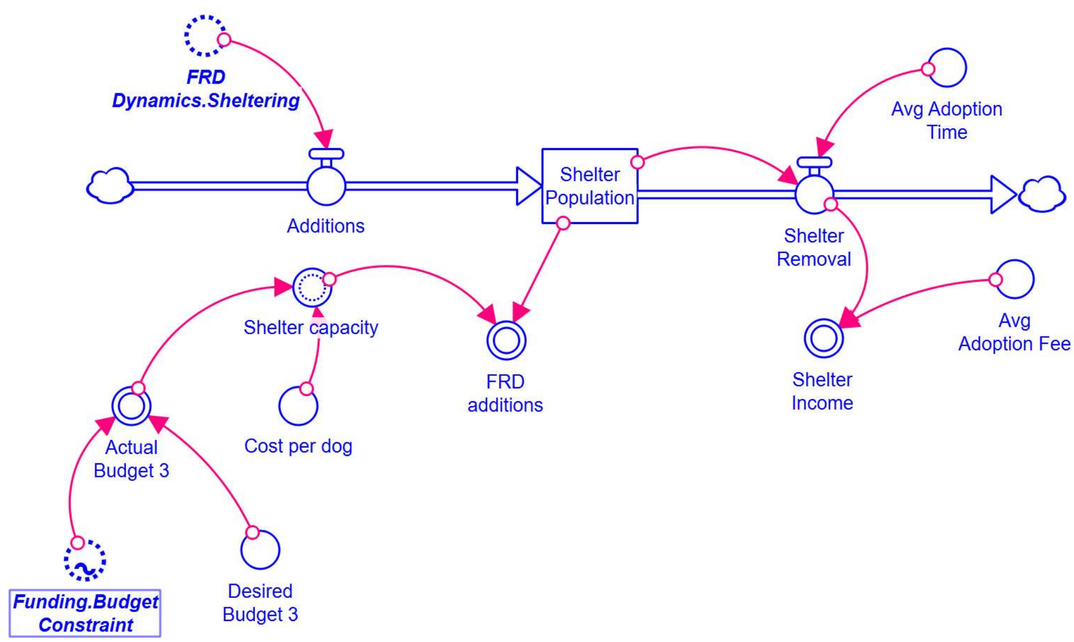


Figure 9. *Shelters* module.

The *Shelters* module shows the third and last of the most prevalently used FRD management strategies. The stock-flow structure defines a *Shelter Population* of FRD who enter via the *Additions* inflow and exit via *Shelter Removal*. Once the user defines the *Desired Budget 3,* it is multiplied by the *Budget Constraint* to obtain the *Actual Budget 3.* This, when divided by the user-defined *Cost per dog*, yields the total *Shelter Capacity.* In this model, *Cost per dog* considers all expenses needed to house shelter dogs, including employee fees and supplies. *FRD Additions,* calculated based on available capacity in the shelter system, then feeds back to the *FRD Dynamics* module when the shelter policy is activated and results in the *Sheltering* co-flow.

The rate of the outflow is determined by the *Average Adoption time* needed to match an owner to the dog and the *Average Adoption Fee* determines the overall *Shelter Income* per year.

The equations for this module are provided below:

Shelter Population = ∫(Additions – Shelter Removal)dt
Additions = FRD Dynamics.Sheltering
Shelter Removal = Shelter Population / Avg Adoption Time
*Actual Budget 3 = Desired Budget 3 * Funding.Budget Constraint*
Avg Adoption Fee = 1500
Avg Adoption Time = 0.25
Cost per dog = 1000
Desired Budget 3 = 0
FRD additions = Shelter capacity – Shelter Population
Shelter capacity = Actual Budget 3 / Cost per dog
*Shelter Income = Shelter Removal * Avg Adoption Fee*

VII. Social Integration Module

This module shows the proposed social integration policy, which is activated by the user-defined *Desired Budget 4* and is constrained by the *Budget Constraint.* Depending on the *Testing/training cost per dog*, the number of *Dogs accommodated* is determined, which in turn feeds back to the *FRD Dynamics* module as batch sizes for FRD training. These FRD then enter the *Volhardt's Testing* flow via the *Sheltering for training* co-flow or the *Preparing for training* co-flow if they need rehabilitation before training. *Volhardt's Success* defines the average success rate for the Volhardt's aptitude and temperament testing process.

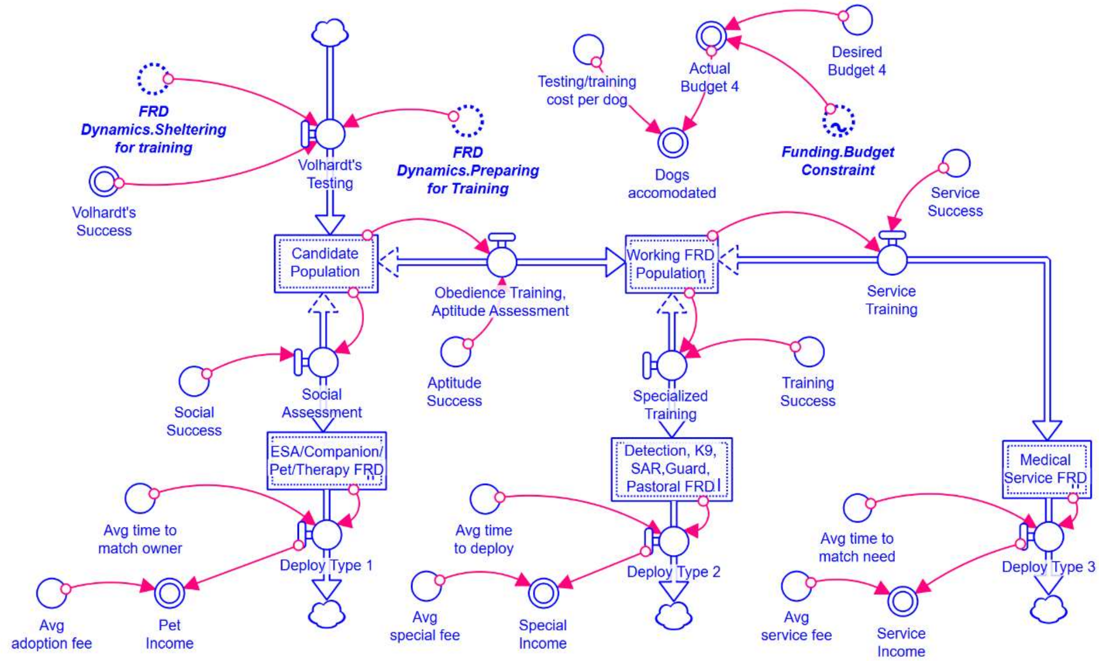


Figure 10. *Social Integration* module.

The successful FRD create the *Candidate Population* stock, from where they either undergo *Social Assessment* or *Obedience Training and Aptitude Assessment* with corresponding success rates. It is assumed in the model that during *Volhardt's testing*, the FRD will be categorized based on their characteristics in companionship, protection, and competition, thereby making further training more targeted. If they succeed, FRD will continue to become *ESA/Companion/Pet/Therapy FRD* or a part of the *Working FRD Population.* With user-defined average success rates for further training, these working FRD will either become *Detection, K9, Search and Rescue, Guard, Pastoral FRD* or *Medical Service FRD*. Dogs in each category will undergo deployment at rates based on time needed to match owners, law enforcement agencies, etc. Income for further FRD population management will occur through *Pet Income, Special Income* for protection-based services, and *Service Income* from deployment of *Medical Service FRD.*

All equations for this module are provided below:

Candidate Population = ∫(Volhardt's Testing – Obedience Training,Aptitude Assessment - Social_Assessment)dt
*Volhardt's Testing = Volhardt's Success * (FRD Dynamics.Sheltering for training + FRD Dynamics.Preparing for Training)*
*Obedience Training,Aptitude Assessment = Candidate Population * Aptitude Success*
*Social Assessment = Candidate Population * Social Success*
Detection,K9,SAR,Guard,Pastoral FRD = ∫(Specialized Training - Deploy Type 2)dt
*Specialized Training = Working FRD Population * Training Success*
Deploy Type 2 = Detection,K9,SAR,Guard,Pastoral FRD / Avg time to deploy
ESA/Companion/Pet/Therapy FRD = ∫(Social Assessment – Deploy Type 1)dt
*Social Assessment = Candidate Population * Social Success*
Deploy Type 1 = ESA/Companion/Pet/Therapy FRD / Avg time to match owner
Medical Service FRD = ∫(Service Training – Deploy Type 3)dt
*Service Training = Working FRD Population * Service Success*
Deploy Type 3 = Medical Service FRD / Avg time to match need
Working FRD Population = ∫(Obedience Training, Aptitude Assessment – Service Training – Specialized Training)dt
*Obedience Training, Aptitude Assessment = Candidate Population * Aptitude Success*
*Service Training = Working FRD Population * Service Success*
*Specialized Training = Working FRD Population * Training Success*
*Actual Budget 4 = Desired Budget 4 * Funding.Budget Constraint*
Aptitude Success = 0.25
Avg adoption fee = 500
Avg service fee = 150000
Avg special fee = 100000
Avg time to deploy = 1
Avg time to match need = 1
Avg time to match owner = 0.25
Desired Budge 4 = 0
Dogs accommodated = Actual Budget 4 / Testing/training cost per dog
*Pet Income = Deploy Type 1 * Avg adoption fee*

*Service Income = Deploy Type 3 * Avg service fee*
Service Success = 0.15
Social Success = 0.75
*Special Income = Avg special fee * Deploy Type 2*
Testing/training cost per dog = 1000
Training Success = 0.2
Volhardt's Success = 0.5

VIII. Funding Module

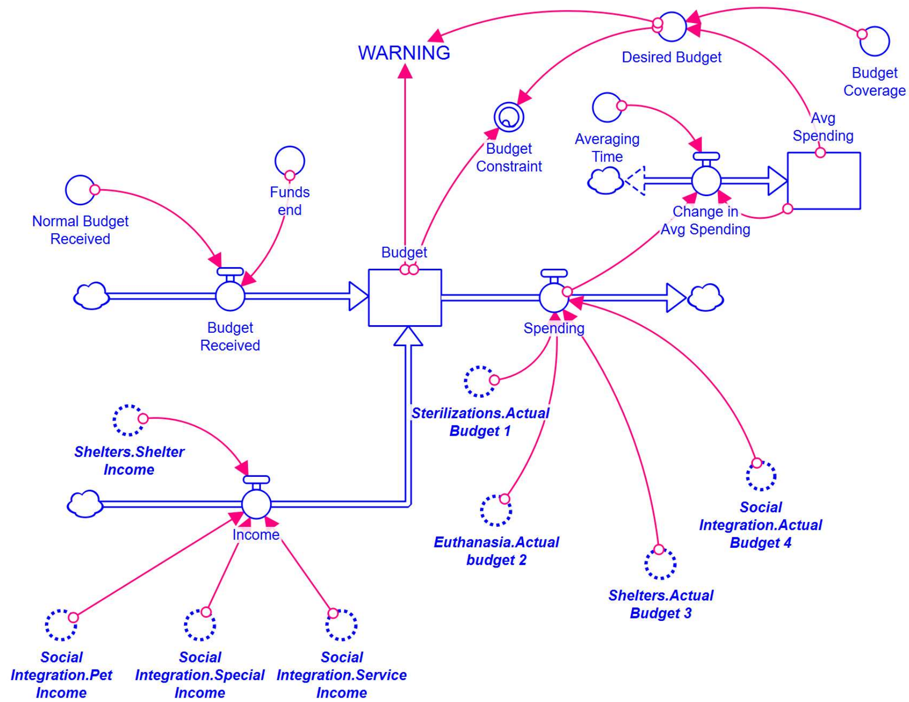


Figure 11. *Funding* module.

The funding module features a central *Budget* stock that is fed by two inflows: *Budget Received* and *Income. Budget Received* depends on the user-defined *Normal Budget Received,* which starts at year 0 and is provided annually until the selected *Funds end* year. The second inflow is determined by the four sources of income from the *Shelters* and *Social Integration* policy modules. The *Spending* outflow occurs using the “Actual budget” values for each of the policies, as they are activated. Since *Spending* can outpace the inflows for *Budget*, there is a *Budget Constraint* embedded in this module that allows limited spending on policies if some, but not all funding exists. The *Budget constraint* is obtained by calculating *Change in Average Spending* and is fed back into each of the policies’ desired budgets.

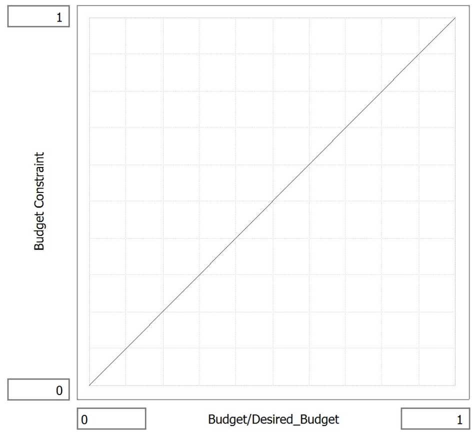


Figure 12. *Budget constraint* defined by ratio of *Budget* to *Desired budget*.

The figure above shows that *Budget constraint* increases from 0 to 1 as *Budget* and *Desired budget* become equal. Finally, for interface users, a *Warning* will show if their *Desired Budget* exceeds the existing *Budget.*

The equations for the module are provided below:

Avg Spending = ∫(Change in Avg Spending)dt
Change in Avg Spending = (Spending – Avg Spending) / Averaging Time
Budget = ∫(Budget Received + Income - Spending)dt
Budget Received = Normal Budget Received - STEP(Normal Budget Received, Funds end)
Income = Shelters.Shelter Income + Social Integration.Pet Income + Social Integration.Special Income + Social Integration.Service Income
Spending = Sterilizations.Actual Budget 1 + Euthanasia.Actual budget 2 + Shelters.Actual Budget 3 + Social Integration.Actual Budget 4
Averaging Time = 1
Budget Coverage = 1
*Desired Budget = 0.00000000001 + (Avg Spending * Budget Coverage)*
Funds end = 10
Normal Budget Received = 100000000
WARNING = Budget / Desired Budget

Gaming Environment Description

The gaming interface created in STELLA provides an opportunity for users to simulate the model without explicitly interacting with the model structure directly. In this game version, users begin by specifying several initial parameters and then progress year by year, observing the current situation and reassessing their policy decisions. Policies are initiated when their corresponding “Desired Budget” is activated to a certain amount.

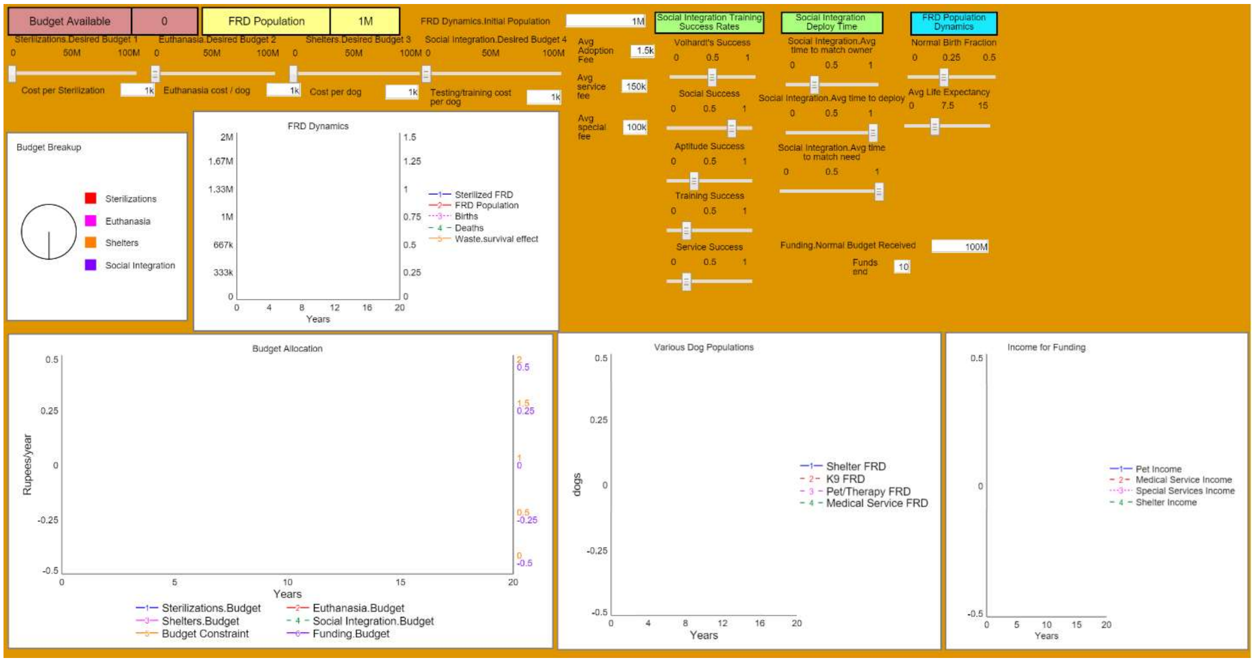


Figure 13. Gaming interface created using STELLA for FRD population management.

At the top left, there are two numeric displays that show *Budget Available* and *FRD Population,* which are stocks in the *FRD Dynamics* and *Funding* modules, respectively. There is also a numeric input for the user to give the *Initial Population* for FRD. Below the numeric displays, there are sliders for the *Desired Budget* pertaining to each of the four policies, with the cost of implementing that policy per dog given below as a numeric input. To the right of the sliders, there are three numeric inputs where the user can define *Average adoption fee, Average service fee, and Average special fee* per dog, obtained through policy implementation. The next group of sliders, for Social Integration Training Success Rates, allow the user to select success rates for each step of the Social Integration policy. This is user-specific because experienced trainers and greater infrastructure in certain countries may result in more successful training at different stages of training. Next, the Social Integration Deploy Time sliders each identify number of years (0-1) needed to deploy FRD as pets, as working dogs, and as service dogs. The final set of sliders allow the user to set FRD Population Dynamics specifics in terms of *Normal Birth Fraction* and *Average Life Expectancy,* which can change between countries, regions, and urban versus rural areas. The numeric inputs below these sliders are used to specify *Normal Budget Received,* as well as a year value for when *Funds end.* In this model, the normal budget is implemented from year 0.

For all graphs on the interface, the x-axis denotes time in years 0 to 20, while the y-axis follows the range of values specific to the simulation. The right axis is consistently used for outputs requiring a smaller range of values. The pie chart at the top left shows the budget breakup based on the Actual Budgets from each of the policies. The graph to its right shows output from the *FRD Dynamics* module as well as *Survival Effect*. The graph below it shows actual budget allocation for all four policies, as well as the available *Budget* and *Budget constraint* from the *Funding* module. The next graph shows the populations of working dogs created from channeling them out of the main FRD population stock, while the last graph shows the resulting yearly income obtained from adoption fees.

This model was calibrated using the Indian FRD case study, and therefore shows currency in Rupees. While running a simulation on the interface, there will be a warning at each time step when the total desired budget from all policies together exceeds the Budget Available, saying “Warning: Your desired budget exceeds the available budget!”. The aim of the game is to lower the main FRD population as quickly as possible, with also the highest number of various working dog populations at the end. These must be accomplished without having policy budgets exceed the available budget.

Simulation for Policy Analysis

The simulation can be run with or without yearly time steps, although reassessment of parameters can only be done if time steps are allowed. To allow for adaptive integration, the model has been set to the classic Runge-Kutta (RK4) method, with a fractional dt value of 1/20.

I. Baseline Run

This simulation will show the baseline run of the model, without any policies implemented. Default parameters have been used in the *Funding, FRD Dynamics,* and *Waste* modules, as can be seen below.

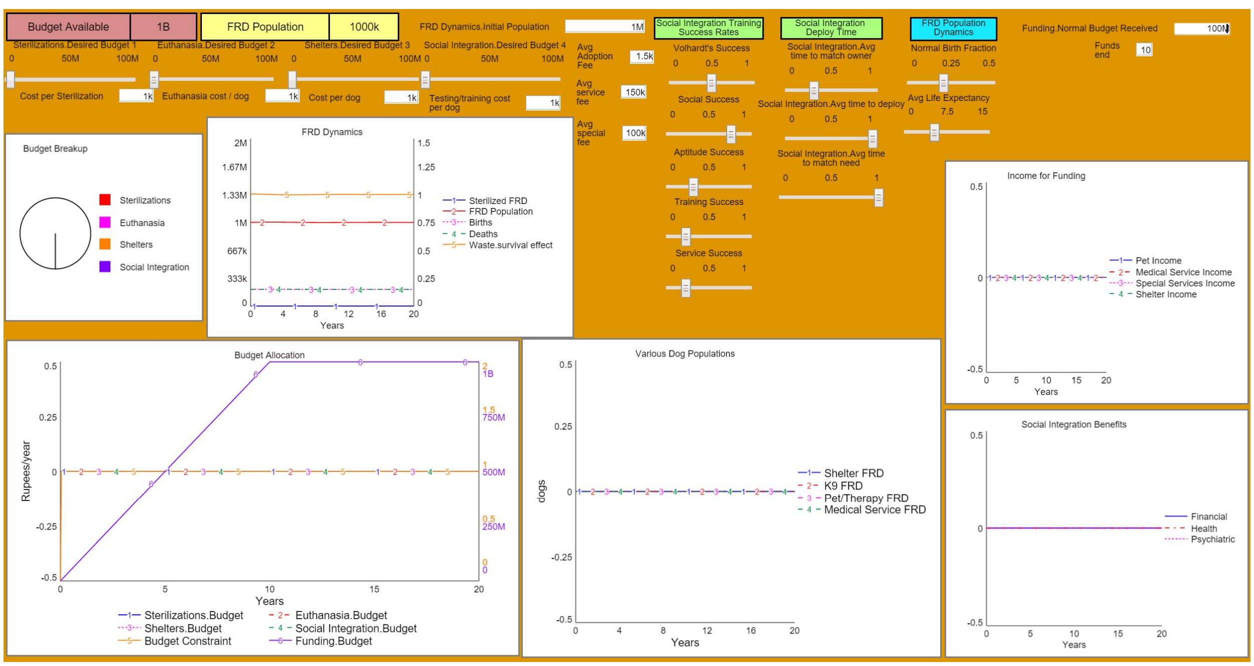
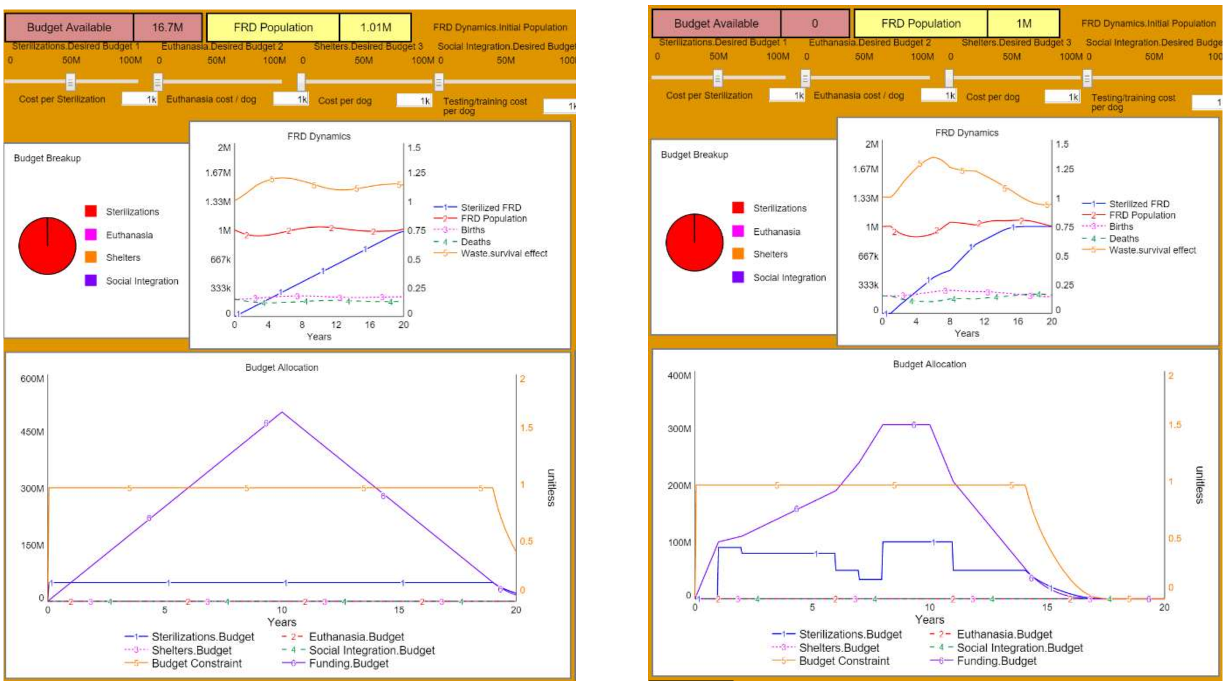


Figure 14. Simulation baseline run.

Run over 20 years, the FRD population remains at the steady one million initial value and the budget accumulates for the set 10 years. Since all desired budgets are at zero, FRD population does not change, various dog populations are not established, and there is no income for funding. In this situation, the *Births* and *Deaths* flow in the *FRD Dynamics* module equal each other, and therefore the FRD population does not waver.

II. Sterilization Policy

When the sterilization policy is activated, the resulting behavior is seen to be the same as in Saeed (2009). Sterilizing the FRD population equals a reduction in birth rate, which initially causes a slight decline in population. However, there is a quick rebound and the population rises again to an even higher number than before and finds equilibrium again due to its goal-seeking behavior.



(a) (b)

Figure 15. Sterilization simulations with constant (a) and varying budget allocations (b).

In the first simulation above, a steady *Sterilization.Desired Budget 1* of Rupees 50M was selected for years 1-20 and the budget was exceeded at year 19. This shows that sustaining a consistent policy for up to almost 20 years does not have its intended effect. Moreover, there are no means to support the budget which is provided until year 10. The second figure shows that even selecting different sterilization desired budgets of 90, 80, 40, etc. does not change this regulatory behavior.

III. Euthanasia Policy

The euthanasia policy significantly mirrors the sterilizations policy in that it affects the death rate exactly as the sterilizations policy affects the birth rate. Therefore, we can expect to see a similar oscillating and goal-seeking pattern in the FRD population graphs, as well as a budget crash around year 19.

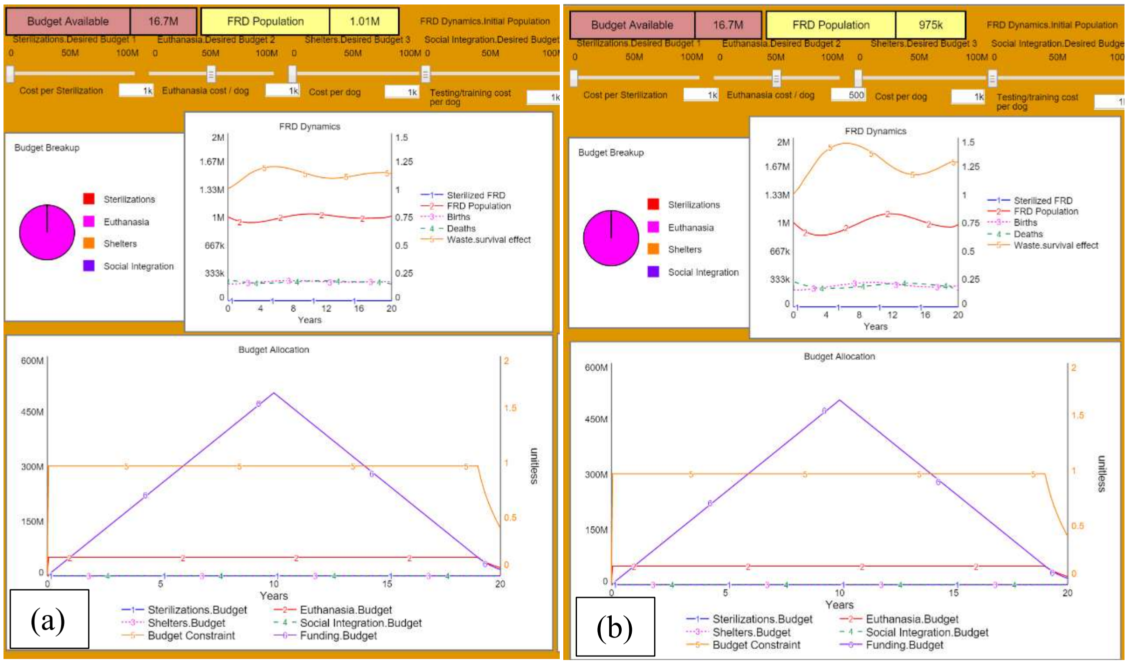


Figure 16. Simulating constant euthanasia (a) and constant policy with reduced cost per dog (b).

Since it can be argued that euthanasia or culling is much cheaper that sterilization surgeries or medicine, the second graph above shows a simulation with half the price (Rupees 500) per euthanasia. However, the same behavior can be noticed, only with high amplitudes than before.

IV. Shelters Policy

Implementing a shelter policy allows revenue to be generated in addition to FRD removal for adoption. The shelter policy can be activated at a higher rate throughout the simulation because it is able to support itself through adoption income. Two example simulations are shown below.

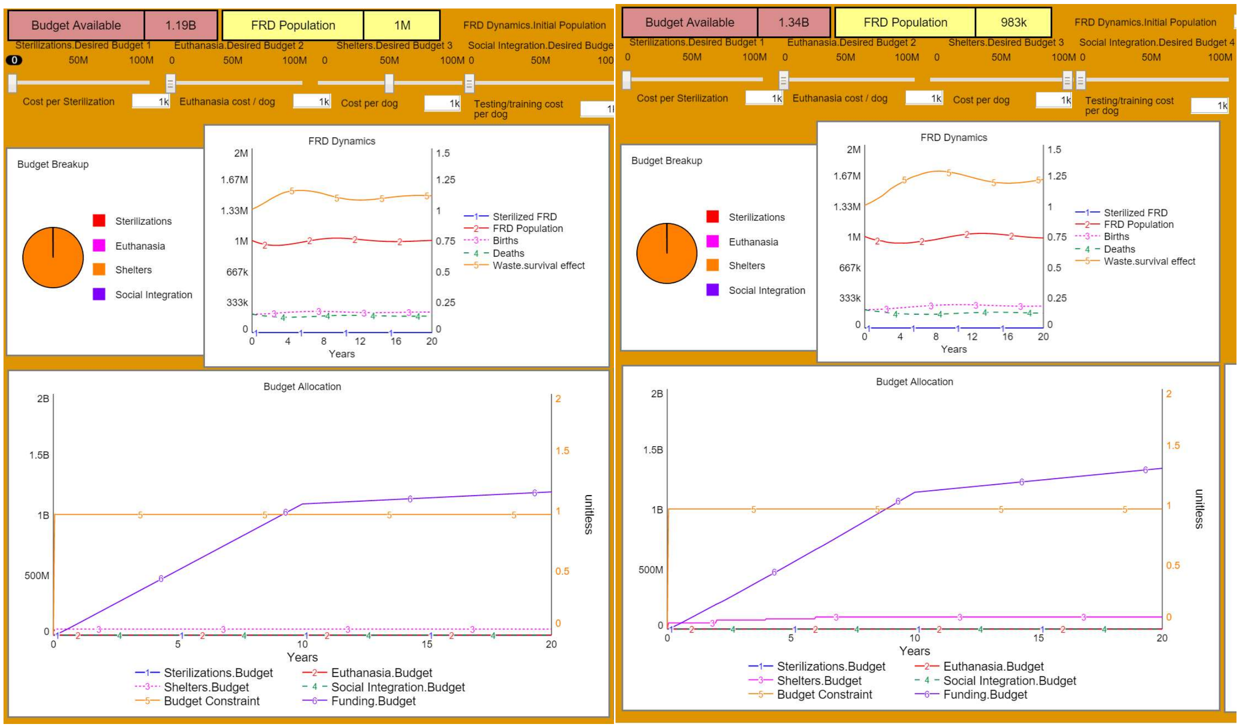


Figure 17. Simulations of shelter policy with constant (a) and varying budget allocations (b).

Figure 17a above shows that even though funding ends by year 10, the budget consistently increases due to the income generated. There is much greater potential here for policy implementation; however, the FRD population graph shows similar goal-seeking behavior by year 20. Figure 17b begins to show the benefits of strategically selecting budget allocations from 50M to 75M, 85M, and 100M. Here, the budget sustains itself even better and also shows a decrease of 17K in the FRD population, instead of purely goal-seeking behavior.

V. Policy Combination with Social Integration

In this model, the *Social Integration* module cannot be activated without either previously or concurrently activating the *Sterilizations* policy, as working FRD will need to undergo this procedure before they are placed into training. Although there are known negative effects of sterilization such as increased territorial behavior and health issues, sterilization has still been included since it is still the norm and requires generous funding.

The first simulation shown below uses various combinations of budget allocations of sterilization and social integration.

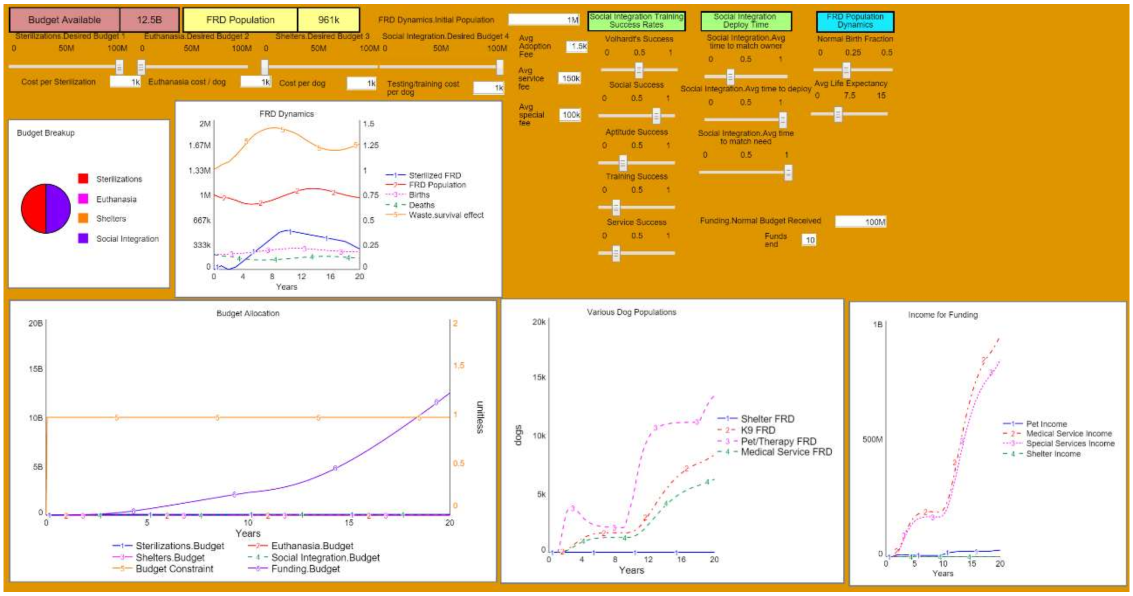


Figure 18. Simulation of *Sterilization* and *Social Integration* polices with variation in budget allocations.

The simulation above was done by alternating focus on sterilization and social integration. For example, sterilization budget was initially set to 25M, while social integration budget was set to 50M, in order to generate a revenue stream early on. This allowed the income stream and budget to quickly rise, allowing stronger sterilization focus for the following year, at 50M. The two policies were alternated until budget began to grow with increasing slope, at which point both policies created a synergy. However, although the amplitude of the oscillation in FRD population increased, to occasionally yield numbers as low as 876K, they could not be sustained using this policy. Social integration creates revenue, but it does not directly remove FRD from the stock population. The next simulation uses shelters as an additional way of removing FRD from the existing population.

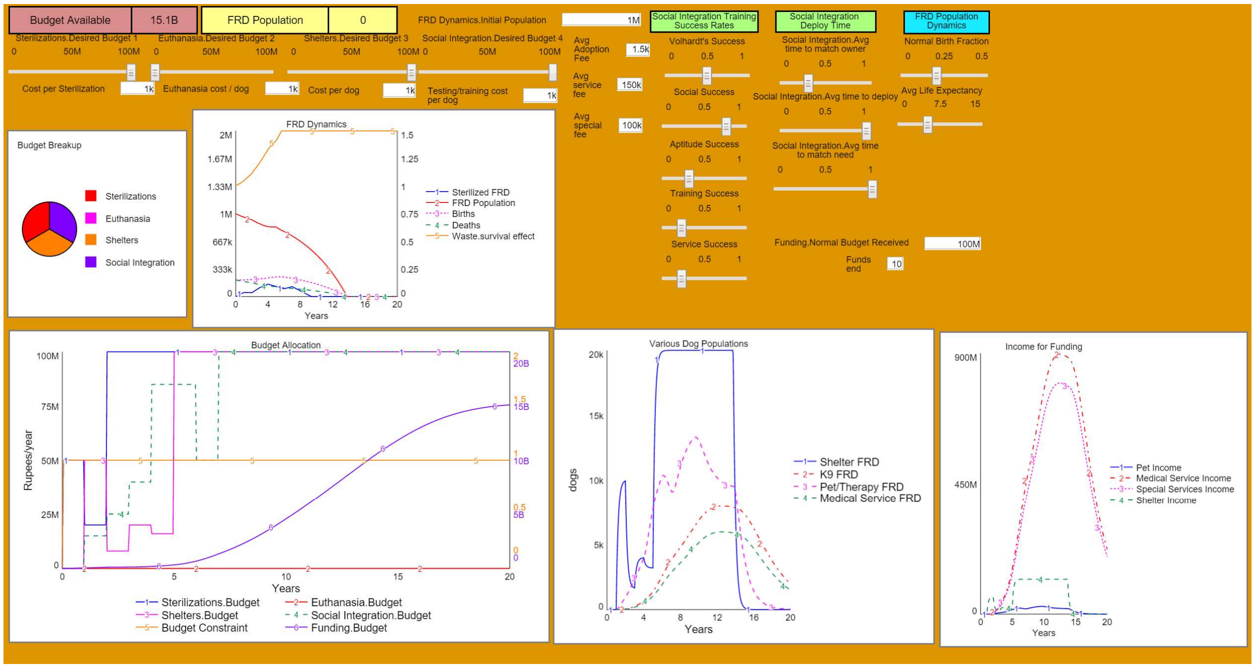


Figure 19. Simulation of combined policies with effective results.

As can be seen in the figure above, this combination of policy yields an increasingly steep decline in FRD population over time. The tactic that was used to plan this intervention was to quickly raise revenue early in the years so that as the *Survival effect* intensifies with FRD removal, increased sterilization and shelter policies can be implemented. The social integration and shelters policies greatly help to create significant populations of shelter FRD (adopted), Pet/Therapy FRD, K9 FRD, and Medical Service FRD. The “Various Dog Populations” graph follows the model closely, since the accumulation of different dog work categories parallels their difficulty in training and chance of success. However, income generation is highest from Medical Service FRD, since they require the longest and most intense training, followed by Special Service FRD, Shelter FRD, and finally Pet FRD.

Design Improvement

There are many areas in which this model can be further advanced. Within the main *FRD Dynamics* module, birth fraction and life expectancy values are the same for all members of the FRD population, whereas they may greatly differ between rural and urban territories. For example, FRD have a greater risk of accidents, human abuse, and harmful food ingestion in cities, whereas FRD are more likely to hunt and consume wildlife and stray from human settlements in rural areas. These vast lifestyle differences can have serious implications on disease, anthropogenic influences, and survival challenges for FRD.

For this model, the waste removal policy identified by Saeed (2009) has not been included, although the *Waste* module is still included to show the effect of *trash food availability* on FRD *fraction births* and *life expectancy.* As discussed in Saeed (2009), the waste removal policy is particularly useful in the Thailand case since the local social behavior deems it proper to not finish one’s food and feed the leftovers to stray animals or discard entirely. Bangkok’s waste removal policy therefore can largely target food vendors and restaurants, who create large amounts of exposed trash, whereas in many countries such as India, the problem of waste food availability comes equally from a variety of sources, such as poor household waste practices, open sewage areas, and exposed dump/landfill sites. For a waste policy to be implemented in India, it would need immense concentrated effort and funding, which is unrealistic in current times. Another reason why this policy has not been included is that removing the only source of food for stray animals in a human-FRD dense country such as India deprives the current FRD population of food essential for survival and is therefore disregarding animal welfare. During the COVID pandemic, it was widely observed that FRD in India were severely lacking food due to reduced trash availability, resulting in severe widespread malnutrition. Competition for food also causes greater territorial behavior, which is harmful for both the FRD and humans in an area, depending on the level of food availability.

The *Waste* policy also consists of one major caveat, in that *trash food availability* is not the only variable that influences *survival effect*. Other major parameters that can be included in an extended model are human density and prevalence of vehicles. However, *trash food availability* is a good indicator for the other parameters since the level of exposed trash increases as human density and transportation infrastructure increase.

The interface can also be further advanced to provide more real-time information for the player. At the end of the game, the user should be able to see the total amount of money they have spent, as well as the time it took for them to lower the FRD population to see how their simulation trials compare. The interface could be improved by embedding a metric that is shown at the end of the game, based on *Budget* spent, income earned, and FRD population management.

Conclusions and Further Implications

The simulations show that there is complex behavior in how the FRD population dynamics counteract efforts to control their population. Various policies have different effects, for varying periods of time, and can be tactically combined to counteract these dynamics and produce a successful intervention. Simulating various combinations of these policies, with user-specified parameters, can be particularly helpful for policymakers who have measured values at hand but cannot make long-term plans with confidence. One of the most important lessons from this model may be, however, that FRD populations must be regularly surveyed so that accurate numbers can be used to simulate the model. Many countries still lack these values, and as can be seen from the simulations, slight differences can drastically change the outcomes of policies. Also, an important lesson from the year-by-year assessment feature in the gaming environment is that one must strategically time their policies to reap the most benefits in the long term.

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Appendix

Model Equations from STELLA:

Top-Level Model:

Euthanasia:

Actual_budget_2 = Desired_Budget_2*Funding.Budget_Constraint

Desired_Budget_2 = 0

"Euthanasia_cost_/_dog" = 1000

"FRD/_Year" = Actual_budget_2/"Euthanasia_cost_/_dog"

FRD_Dynamics:

FRD_in_Rehabilitation(t) = FRD_in_Rehabilitation(t - dt) + (Rehabilitating - Preparing_for_Training) * dt
INIT FRD_in_Rehabilitation = 0
INFLOWS:
Rehabilitating = Social_Integration.Dogs_accomodated*(1-Social_Integration.Volhardt's_Success)
OUTFLOWS:
Preparing_for_Training = FRD_in_Rehabilitation/Avg_time_for_rehab
FRD_Population(t) = FRD_Population(t - dt) + (Births - Deaths - Sterilization - Sheltering) * dt
INIT FRD_Population = Initial_Population
INFLOWS:
Births = FRD_Population*Fraction_Births
OUTFLOWS:
Deaths = FRD_Population/Life_Expectancy + Euthanasia."FRD/_Year"
Sterilization = Sterilizations."FRD/_Year"
Sheltering = Shelters.FRD_additions
Sterilized_FRD(t) = Sterilized_FRD(t - dt) + (Sterilization - Sheltering_for_training - Rehabilitating) * dt
INIT Sterilized_FRD = 0
INFLOWS:
Sterilization = Sterilizations."FRD/_Year"
OUTFLOWS:
Sheltering_for_training = Social_Integration.Dogs_accomodated
Rehabilitating = Social_Integration.Dogs_accomodated*(1-Social_Integration.Volhardt's_Success)
Avg_Life_Expectancy = 5
Avg_time_for_rehab = 0.5
Fraction_Births = Normal_Birth_Fraction*Waste.survival_effect
Initial_Population = 1000000
Life_Expectancy = Avg_Life_Expectancy*Waste.survival_effect
Normal_Birth_Fraction = 0.2

Funding:
Avg_Spending(t) = Avg_Spending(t - dt) + (Change_in_Avg_Spending) * dt
INIT Avg_Spending = 0
INFLOWS:
Change_in_Avg_Spending = (Spending-Avg_Spending)/Averaging_Time
Budget(t) = Budget(t - dt) + (Budget_Received + Income - Spending) * dt
INIT Budget = 0
INFLOWS:

Budget_Received = 0 + Normal_Budget_Received - STEP(Normal_Budget_Received, Funds_end)
Income =
Shelters.Shelter_Income+Social_Integration.Pet_Income+Social_Integration.Special_Income+Social_Integration.Service_Income
OUTFLOWS:
Spending =
Sterilizations.Actual_Budget_1+Euthanasia.Actual_budget_2+Shelters.Actual_Budget_3+Social_Integration.Actual_Budget_4
Averaging_Time = 1
Budget_Constraint = GRAPH(Budget/Desired_Budget)
(0.000, 0.000), (0.100, 0.100), (0.200, 0.200), (0.300, 0.300), (0.400, 0.400), (0.500, 0.500), (0.600, 0.600), (0.700, 0.700), (0.800, 0.800), (0.900, 0.900), (1.000, 1.000)
Budget_Coverage = 1
Desired_Budget = 0.00000000001+(Avg_Spending*Budget_Coverage)
Funds_end = 10
Normal_Budget_Received = 100000000
WARNING = Budget/Desired_Budget

Shelters:
Shelter_Population(t) = Shelter_Population(t - dt) + (Additions - Shelter_Removal) * dt
INIT Shelter_Population = 0
INFLOWS:
Additions = FRD_Dynamics.Sheltering
OUTFLOWS:
Shelter_Removal = Shelter_Population/Avg_Adoption_Time
Actual_Budget_3 = Desired_Budget_3*Funding.Budget_Constraint
Avg_Adoption_Fee = 1500
Avg_Adoption_Time = 0.25
Cost_per_dog = 1000
Desired_Budget_3 = 0
FRD_additions = Shelter_capacity-Shelter_Population
Shelter_capacity = Actual_Budget_3/Cost_per_dog
Shelter_Income = Shelter_Removal*Avg_Adoption_Fee

Social_Integration:
Candidate_Population(t) = Candidate_Population(t - dt) + (Volhardt's_Testing - "Obedience_Training,_Aptitude_Assessment" - Social_Assessment) * dt
INIT Candidate_Population = 0
INFLOWS:

Volhardt's_Testing =
Volhardt's_Success*(FRD_Dynamics.Sheltering_for_training+FRD_Dynamics.Preparing_for_Training)
OUTFLOWS:
"Obedience_Training,_Aptitude_Assessment" = Candidate_Population*Aptitude_Success
Social_Assessment = Candidate_Population*Social_Success
"Detection,_K9,_SAR,Guard,_Pastoral_FRD"(t) =
"Detection,_K9,_SAR,Guard,_Pastoral_FRD"(t - dt) + (Specialized_Training - Deploy_Type_2) * dt
INIT "Detection,_K9,_SAR,Guard,_Pastoral_FRD" = 0
INFLOWS:
Specialized_Training = Working_FRD_Population*Training_Success
OUTFLOWS:
Deploy_Type_2 = "Detection,_K9,_SAR,Guard,_Pastoral_FRD"/Avg_time_to_deploy
"ESA/Companion/_Pet/Therapy_FRD"(t) = "ESA/Companion/_Pet/Therapy_FRD"(t - dt) + (Social_Assessment - Deploy_Type_1) * dt
INIT "ESA/Companion/_Pet/Therapy_FRD" = 0
INFLOWS:
Social_Assessment = Candidate_Population*Social_Success
OUTFLOWS:
Deploy_Type_1 = "ESA/Companion/_Pet/Therapy_FRD"/Avg_time_to_match_owner
Medical_Service_FRD(t) = Medical_Service_FRD(t - dt) + (Service_Training - Deploy_Type_3) * dt
INIT Medical_Service_FRD = 0
INFLOWS:
Service_Training = Working_FRD_Population*Service_Success
OUTFLOWS:
Deploy_Type_3 = Medical_Service_FRD/Avg_time_to_match_need
Working_FRD_Population(t) = Working_FRD_Population(t - dt) + ("Obedience_Training,_Aptitude_Assessment" - Service_Training - Specialized_Training) * dt
INIT Working_FRD_Population = 0
INFLOWS:
"Obedience_Training,_Aptitude_Assessment" = Candidate_Population*Aptitude_Success
OUTFLOWS:
Service_Training = Working_FRD_Population*Service_Success
Specialized_Training = Working_FRD_Population*Training_Success
Actual_Budget_4 = Desired_Budget_4*Funding.Budget_Constraint
Aptitude_Success = 0.25
Avg_adoption_fee = 500
Avg_service_fee = 150000

Avg_special_fee = 100000
Avg_time_to_deploy = 1
Avg_time_to_match_need = 1
Avg_time_to_match_owner = 0.25
Desired_Budget_4 = 0
Dogs_accomodated = Actual_Budget_4/"Testing/training_cost_per_dog"
Pet_Income = Deploy_Type_1*Avg_adoption_fee
Service_Income = Deploy_Type_3*Avg_service_fee
Service_Success = 0.15
Social_Success = 0.75
Special_Income = Avg_special_fee*Deploy_Type_2
"Testing/training_cost_per_dog" = 1000
Training_Success = 0.2
Volhardt's_Success = 0.5

Sterilizations:
Actual_Budget_1 = Desired_Budget_1*Funding.Budget_Constraint
Cost_per_Sterilization = 1000
Desired_Budget_1 = 0
"FRD/_Year" = Actual_Budget_1/Cost_per_Sterilization

Waste:
Trash_Food(t) = Trash_Food(t - dt) + (Waste_Generation - trash_food_consumption_by_FRD - Trash_Disposal) * dt
INIT Trash_Food = 1000000
INFLOWS:
Waste_Generation = Normal_Waste_generation
OUTFLOWS:
trash_food_consumption_by_FRD = FRD_Dynamics.FRD_Population
Trash_Disposal = units_disposed
Normal_Waste_generation = 1000000
survival_effect = GRAPH(trash_food_availability)
(0.000, 0.010), (0.400, 0.540), (0.800, 0.870), (1.200, 1.140), (1.600, 1.350), (2.000, 1.500), (2.400, 1.500), (2.800, 1.500), (3.200, 1.500), (3.600, 1.500), (4.000, 1.500)
trash_food_availability = Trash_Food/FRD_Dynamics.FRD_Population
units_disposed = 0
{ The model has 109 (109) variables (array expansion in parens).
In root model and 7 additional modules with 0 sectors.
Stocks: 12 (12) Flows: 24 (24) Converters: 73 (73)
Constants: 31 (31) Equations: 66 (66) Graphicals: 7 (7)}