Spring 2018

Green Roof Policy Optimization Algorithms and Microsimulations Benefits and Downsides of Green Roof Incentives and Mandates in San Francisco

Harrison Freund

GREEN ROOF POLICY OPTIMIZATION ALGORITHMS AND MICROSIMULATIONS BENEFITS AND DOWNSIDES OF GREEN ROOF INCENTIVES AND MANDATES IN SAN FRANCISCO

by

Harrison Freund

A thesis submitted in partial fulfillment of the requirements for graduation with Honors in the Electrical Engineering

Scott Spak
Thesis Mentor

Spring 2018

All requirements for graduation with Honors in the Electrical Engineering have been completed.

Xiaodong Wu
Electrical Engineering Honors Advisor

Green Roof Policy Optimization Algorithms and Microsimulations Benefits and Downsides of Green Roof Incentives and Mandates in San Francisco

By

Harrison Freund

A thesis submitted for partial fulfillment of the requirement for graduation with Honors in the Department of Electrical & Computer Engineering

Dr. Scott Spak Faculty Research Advisor

____

Spring 2018

All requirements for graduation with Honors in the Department of Electrical & Computer Engineering have been completed

Dr. Xioadong Wu Electrical & Computer Engineering Honors Advisor

____

Nicole M. Grosland Associate Dean for Academic Programs

____

Green Roof Policy Urban Microsimulations Benefits and Downsides of Green Roof Incentives and Mandates in San Francisco

Harrison L. Freund[1, 2], Scott N. Spak[1, 3]

[1]The University of Iowa Public Policy Center. 310 South Grand Avenue, Iowa City, Iowa 52242.
[2]The University of Iowa, Department of Electrical and Computer Engineering, Iowa City, Iowa. [3]The University of Iowa, School of Urban and Regional Planning, Iowa City, Iowa.

Abstract

As the 21st Century progresses, developers are becoming more aware of their environmental footprint. As the Green Economy slowly gains its footing, developers will be expected to change current building practices to reflect the increasing demand to adapt to sustainability challenges. One such methodology used by LEED to evaluate the sustainability of a building is the implementation of a green roof, the installment of vegetation on the top of a building.

There are many socioecological benefits that justify the implementation of a green roof, which explain why in recent years municipalities have enacted new policies to mandate or incentivize their implementation. Four optimization algorithms were developed to determine the size of a green roof delivering maximum Net Present Value (NPV) based off raw economics, San Francisco policy, Chicago policy, and Toronto policy. The models were then tested on a sample of 2001 random buildings in San Francisco and the results analyzed. The major findings are that incentives as described by the Chicago policy do not increase the amount of green roofing installed, and mandates as enacted by Toronto and San Francisco do not apply to enough buildings to be meaningful.

Introduction and Motivation

Historical and Contemporary Perspective

As a matter of policy, green roofing is newer to metropolitan areas in North America than it is in Europe and Japan. At the turn of the 21st century, Germany and Japan were taking aggressive steps to pursue the implementation of green roofs. Both nations established policies requiring green roof installation, while Germany had some subsidies offered at the local level. However, the City of Sheffield in the United Kingdom was the first city to have an official policy, providing information and bounds regarding green roofing (Dunnett & Kingsbury).

This paper will explore the benefits and drawbacks of both the carrot and stick approach to enacting policies related to green roofing when compared against no action. These tests will be based off policies and actions taken by the cities of San Francisco, Toronto, and Chicago. They will be compared against a baseline model of the economic situation without policy intervention.

Ecosystem Services

Pursuing sustainability goals and with green infrastructure to those ends is a topic of increased interest in the literature (Lovell & Taylor, 2013), however it can be documented in real policy decisions as far back as 2003 by the Atlanta City Council. Green roofs are an example of one such green infrastructure feature, which is heavily cited in the literature as delivering numerous benefits along economic and ecological basses. Green roofs can deliver these benefits because the installation of vegetation on the roof imparts ecosystem services that are delivered directly to the building and the surrounding community (Merrow & Newell). These services include the cultural services from reducing social vulnerability to natural disasters (Merrow & Newell) and increasing access to green space, which is cited as delivering psychological benefits to individuals (The University of Washington, College of the Environment, n.d.).

The Urban Heat Island Effect is a well-documented phenomenon in which the darker nature of artificial surfaces in human environments absorbs more light and results in surface temperatures being 3.6ºF warmer on average (Vargo, Stone, Hebeeb, Liu, & Russell). However, the weighted concern of the Urban Heat Island Effect ranks last on a list of concerns municipalities address with green roof policies (Merrow & Newell).

The mechanism in which the UHE can be alleviated using green roofing comes from their ability to shade the roof and undergo evapotranspiration (United States Environmental Protection Agency, 2011; United States General Services Administration (2011). The shade a roof provides is achieved from the sunlight that plants block from reaching the surface of the building. This can reduce the amount of sunlight reaching the surface by 70-90%, with the remainder being used for biological processes within the plants. Evapotranspiration is the combination of evaporation and transpiration that occurs when water from the roots of a plant are later emitted through their leaves. This in turn cools the building because thermal energy from the air is absorbed into the emitted water to evaporate the water instead of performing thermal work on the building (United States Environmental Protection Agency, 2011). This in turn provides reduction on utilities bills and is how green roofs can achieve a return on investment.

Storm water abatement is the primary motivation for cities and municipalities to pursue widespread usage of green roofs. On all indicators, storm water abatement is the most important to developers and experts on the ground (Merrow & Newell). This is also demonstrated in realworld policy justifications, such as a San Francisco Memorandum citing rising sea-levels and increasing storm water management costs for the city as reason to mandate green roofing on certain genres of development (San Francisco Board of Supervisors). These justifications are substantiated by studies showing that extensive roofs can capture 50 to 100% of incoming rain, whereas the thicker intensive class of green roofs will capture even more rain. These benefits are variable based on locality, however they are shown to increase as the plants mature (United States Environmental Protection Agency, 2011).

The improvements made in storm water abatement (United States Environmental Protection Agency), the reduction of the UHE, as well as additional benefits such increased habitat connectivity and green space (Merrow & Newell) are examples of ecosystem services provided with this development strategy. The EPA classifies the benefits of green roofing falling into public and private categories. Since the green roof delivers numerous ecosystem services that have monetary and personal value to humans, they are an example of a multifunctional landscape feature within the urban environment (Lovell & Taylor). However, since ecosystem services are not monetized in our actual economy, they are not considered in our models unless they impart direct economic benefit (such as enhanced insulation) onto developers. Still, these aspects of green roofs provide motivation for cities to pursue their further development and deployment.

Economics

The economics of green roof will be the driving force regarding the simulation. Figures for the cost of installing a green roof vary, however the Environmental Protection Agency estimates cost varies from $10/sq. ft. ($0.93/sq. m.) to $25/sq. ft. ($2.32/sq. m.) (United States Environmental Protection Agency, 2011), whereas other estimates assume costs between $18/sq. ft. ($1.87/sq. m.) and $25/sq. ft. (City of Chicago Department of Water Management, n.d.). While these ranges have different figures, both sources reported that the cost is variable primarily with the degree of intensiveness of the roof, with more intensive roofs offering higher performance at a greater cost. (United States Environmental Protection Agency, 2011). Cost is also observed to decrease as the amount of roof cover increases (United States General Services Administration, 2011). Over the typical 40-year lifespan of a 2000 sq. m. (21527.82 sq. ft.) green roof, direct economic benefits are estimated at $200,000 ($0.23/sq. ft./yr.), with almost 67% coming from the reduction of energy costs. In 2011, the United States General Services Administration found that the additional annual maintenance cost ranges from $0.21 to $0.31 per sq. ft.

An additional economic benefit is that the roof will last twice as long, which avoids the cost of installing a new roof twice as often (United States Department of the Interior National Park Service, n.d.). Further, the EPA estimates that most green roofs begin returning on their investment in around six years (United States Environmental Protection Agency, 2011). However, the cost of a conventional roof is estimated to be half of that of a green roof installation. The implications of this information on the assumptions made and how the model was constructed will be discussed.

Past literature in urban micro-simulation have not considered the fact that municipalities operate as complex systems. Every city consists of a government with numerous branches and offices, various private sector businesses that compete with one another, and a population that displays some degree of variance in terms of prosperity. The forces that causes these phenomena all interact with one another (Meadows, 2008). A police station for public safety, business and industry for capital, and a population that varies in income, power, and privilege have different priorities. Using simulation software is an avenue to understand the systems that make up cities. The method presented in this paper will delineate the manner in which offline calculations can be fully integrated into the UrbanSim simulation engine to measure the consequences of these decisions more broadly. This would allow inspection of the policy decision as a flow of the larger system, perhaps enabling the detection of a fundamental signal.

Since the simulation software assumes a rational choice model on the developer level (Waddell, 2002), participation where optional would assume only the personal benefits of a green roof. It also assumes that the user has complete access to accurate information, which is supplied in the executed code. UrbanSim only delivers economic data, which is assumed to be the main driver of individual choices (Green, Kronenberg, Andersson, Elmqvist, & GomézBaggethun, 2016). However, sometimes decisions are made for reasons other than money.

Project Questions

Given the benefits green roofs offer to developers and to municipalities, there are many questions that arise when thinking of increasing their usage through policy. The following are questions that the project aims to address:

- What are the expected impacts of implementing Green Roof Mandates and Incentives?
- How effective are green roof mandates in increasing the utilization of green roofs and delivering their benefits?
- How effective are green roof incentives in increasing the utilization of green roofs and delivering their benefits?
- What are the economic impacts associated with the increased utilization of green roofs?

Project Thesis

If the simulation results run as expected, there will be two main points. The first is that there will an increase in the amount of green roofing installed, however there may be undesirable effects economically as development costs increase. This represents the point of view from conventional decision makers in the United States. What is being explored is the accuracy of that point of view considering the alternative point of view that green roofs will provide a positive Net Present Value (NPV) and that these policies will aid in that. The policies being explored are summarized in Table 1. A more detailed description is provided in the subsequent paragraphs.

Table 1: Policy summaries tested (San Francisco Board of Supervisors; San Francisco Planning

Department), (City of Chicago Department of Buildings, n.d.), and (City of Toronto Planning & Development, n.d.)

Policy Case	Description
No Action	Considers only the direct economics of green roof installation using available data.
San Fran	Mandates the installation of green roofs on all buildings shorter than 6 stories for nonresidential purposes. Exception for computing centers cannot be tested now.
Chicago	Provides a 5¢ discount on permit fees per square foot of green roofing installed.
Toronto	Mandates the installation of green roofs except residential buildings following the size gradation detailed in Table 2.

Green Roof Mandate (San Francisco)

This model requires the installation of a green roof on all new development with exceptions made for single family residential homes. Therefore, the implementation of green roofing would be expected to drastically increase since it is a prerequisite for obtaining a building permit (San Francisco Board of Supervisors; San Francisco Planning Department).

Green Roof Incentive (Chicago)

The City of Chicago has developed a Green Roofing Program, wherein by developing a green roof yields a discount of $0.05 per square foot of green roofing (City of Chicago Department of Buildings, n.d.). This would be an added step that developers would go through in the process of getting the permit approved for their building (City of Chicago Department of Buildings, 2012). This model does not require any action from the community but would still be expected to increase the implementation rate of green roofing because some developers would find it advantageous to buy into such a program.

Test 3: Green Roof Mandate by size (Toronto)

This model requires the installation of a green roof on all new development specifying a minimum size based on the size of the roof (City of Toronto Planning & Development, n.d.). These requirements are described in Table 2. Green roof development is expected to dramatically increase as a result, however since the minimum size specifications act as a floor, testing would see if simulated installation would exceed the minimum requirements.

Size of Building (ft^2)	**Size of Green Roof**
<21524	0%
21525-53799	20%
53800-107624	30%
107625-161449	40%
161450-215274	50%
>215275	60%

Test 4: No Intervention Case

This model will be a simple simulation running no added enactments of mandates or incentives. The only code added involves economic features of green roofs removed from government actions.

The following output variables will suffice to answer the project questions: number of green roofs installed, total area of green roofs installed, and the NPV of green roofs installed. These variables can be generated or derived from output created by the code in the Appendix A predicted to behave as summarized in Table 3.

Table 3: Expected results from tests

Variable	**Expected Behavior**
Number of Green Roofs Installed	The total number of green roofs installed is expected to rise. This is because in the cases of mandates, owners will be forced to install some minimum size based on the mandate or the economic incentive will improve the NPV of the investment.
Total Area of Green Roofs	The total area of green roofs installed is expected to rise. This is because either through force or more

	attractive economic conditions, there will be overall greater installation of green roofs.
NPV of Green Roofs	The total NPV of green roofs is expected to rise in the case of the incentive because the fee reduction Chicago offers is a direct benefit to developers. There is a possibility that the mandate will force an developer to install a green roof when it is impractical.

The main expected result is that regardless of what is pursued, the installation of green roofing will become more prevalent. It is predicted that incentive will provide a greater increase than if the market were to act on its own, whereas mandates would guarantee a certain increase which is predicted to be even greater than incentive strategies.

Methods:

This project was implemented using UrbanSim as a micro level simulation software at the building level. To evaluate the impact of the green roof policies, a baseline simulation was run with evaluating the number of green roofs without any modifications to current practices. This means that there were no incentives or mandates regarding green roofs. This baseline simulation acts as a control. The proposed policies were then written into code and simulated in this framework. This code was generated with the code of Appendix A. The simulation only provides data about economic outcomes resulting from the policies and the number of green roofs implemented based on whether it was in the economic interests of the developer to install one where optional.

Since costs decrease as they bought in larger quantities, green roofs are observed to have a per area cost reduction as a function of their size (United States General Services Administration, 2011). A graph from the United States General Services Administration in 2011 was digitized so its data could be placed into Excel. The data was then modeled using a power model function. The data as well as the graph of the model is shown. The model reported a cost size relation of y = $38.951x^{0.081}$ with R^2 = .9909 for Semi-Intensive Green Roofs. The model reported a cost-size relation of y = $23.907x^{0.078}$ with an R^2 = .9933.

Table 4: Data points used to generate economies of scale model (United States General Services Administration, 2011)

Square Feet	**Semi-Intensive Cost per Sq. Ft.**	**Extensive Cost per Sq. Ft.**
5000	19.60	12.37
10000	18.20	11.55
50000	16.18	10.30

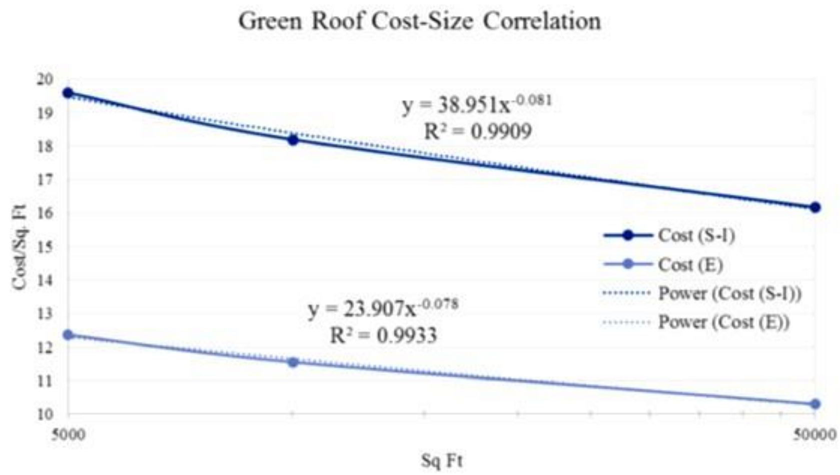


Figure 1: Economies of scale for green roofing based on size

This model is accurate to real world data because it is operating under the same assumption of economies of scale (The University of Pennsylvania, The Wharton School, n.d.). This theory states that the cost per unit will decline as a function of the units. This idea follows a power model quite accurately because as the unit size increases, the rate at which the cost per unit declines will also decline. In the situation of the green roof, we can assume that these limitations are caused by such factors such as the rate of decline in purchasing raw materials declines as well, increased labor costs as additional persons are needed for larger, projects, and other factors.

For this simulation, we are only considering the extensive green roofing system because it dominates the market when compared to intensive green roofing systems. This is because the extensive green roof has a lower cost per square foot. This is important to the simulation because it assumes that the user will select the most rational option, which in this case would be the extensive roof because it delivers similar concrete and tangible benefits for a lower cost per square foot. The simulation does not consider the intrinsic value of being around trees, flowers, and other such plants that intensive roofs allow because such value is not rational from the economic perspective of the simulation. The algorithm assumed that these capital costs would start at a base of $12 per sq. ft, twice the rate of a conventional roof, with an adjustment for the tested sizes occurring based of that.

With data about the expected lifecycle of a green roof being about 40 years, the economic rationality of installing a green roof can be assessed. We do this by calculating the benefits and adding the cost of a roof installation at year 20 had a grey roof been used for the building instead. We make this assumption because green roofs are known to last two times longer than their conventional counterparts. If this sum exceeds 0, it indicates that installing some green roof is rational.

The results of this calculation should not be taken purely at their face value because it assumes that their access to information as reliable as the model allows, which in the real world is usually access to lower quality information and assumption. Another important limitation regarding our analysis of the green roof policies is that they assume that all the roofs are flat and have areas on them that can support such development. Heavily slanted roofs are not suitable for green roofs because of high levels of drainage. Governmental sources stat that slope grades greater than 20% (Prince George's County Department of the Environment, n.d.) and 25% (Tennessee Department of Environment and Conservation & University of Tennessee, 2014) are the maximum steepness for extensive green roofing to be effective. Our study does not consider loss of benefits or increased costs associated with installation of green roofs on roofs that are not suitable to them and treats all roofs as flat and able to hold green roofs.

Another important assumption is that retrofitting a roof is very difficult and would require such extensive reconstruction that simulating it did not seem useful. This is because most existing buildings are not able bear the load of a green roof since they are much heavier than a conventional roof. This means that to retrofit exist construction with a green roof, one would need to completely reevaluate the structural integrity of a building and make drastic changes to its support systems. This comes at a high cost burden to the owner in additional to the capital investment required for a green roof itself. This assumption conveniently reflects the simulation's ability to only address new development when fully integrated. (S. Spak, personal communication, 2017). The scope presented here also only considers existing buildings and imagines that they are proposed for the purposes of testing the algorithms, although the mechanism to test on new construction was prepared and will be described.

UrbanSim also uses NPV to determine its outcomes. We discuss the possibility of considering other factors for reasons that will be explored in detail in the Discussion Section. However, we followed UrbanSim's NPV paradigm. The model that was implemented accessed data from an HDF-5 file (which stores many tables). This file contained the building square footage, the number of stories, and the overall use of the building (residential, industrial, office, etc.). These data points were used as parameters for specially defined functions that use the policies and figures previously outlined to compute the rationality of a green roof being installed.

Results

Early versions of the model were tested with various fictional parameters. It was observed the, green roofs generated an economic gain for a building over a 40-year period. It was also observed that buildings were generally able to recover their costs in about 7 years, as previously cited by sources. This meant that the fundamentals of the model had some basis. It was also observed that the economic advantage of green roofs meant that in all scenarios, initial utilization rates were high.

The results presented here will focus on a set of 2,001 buildings selected from the San Francisco database. The results were culled by taking in the square feet and the number of stories as parameters into the optimization algorithms and computing the ideal size of a green roof for that building, the cost that are incurred at the 20-year mark to replace a conventional roof, and the benefit and cost of the project over its estimated 40-year life, as well as a flag that detected if some coverage amount would be a net benefit over no installation. Other flags were raised if needed, such as if a mandate applied in the San Francisco or Toronto tests. The results from these individual calculations were then written to an Excel file, where further analysis was taken. The tests showed that a 24% area coverage was optimal. This is not to say that more coverage could not return a net benefit, but that the benefit at 24% coverage was highest. The reason is NPV is calculated by the difference between a benefit curve and a cost curve. The point where the difference between benefit and cost is greatest with benefit greater than zero is optimal. Since there are many parameters in the equations that can change rapidly with economy and policy, it is better to focus on the overall behavior of this relationship. This fundamental relationship is expressed in Figure. The relationship is between the size and financials of a project, with the size representing the proportion of the roof area (0 being no roofing and 1 being the entire area used for green roofing). The blue curve represents the financial benefits of a green roof installation, whereas the red curve represented the cost. The black line between the two represents the NPV of the project at the optimal size, which is denoted by a vertical line.

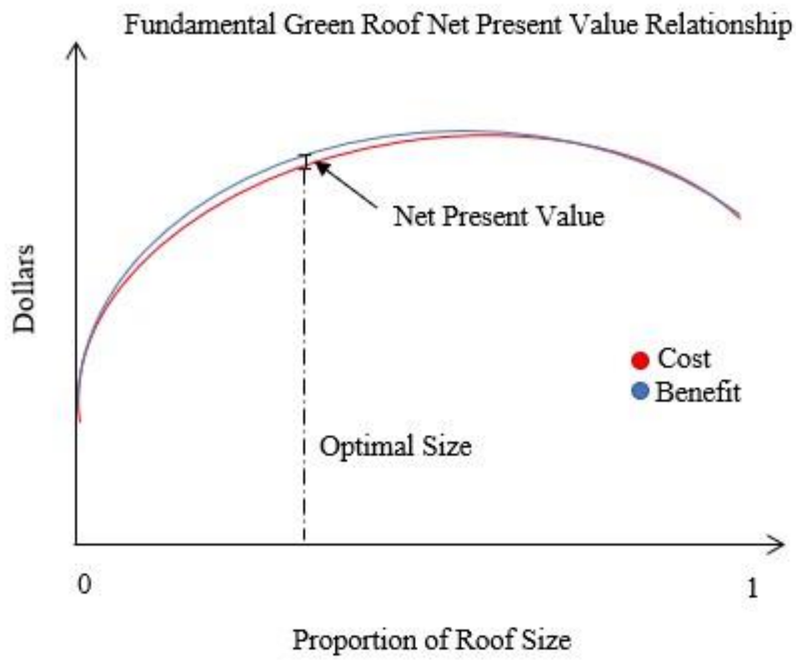


Figure 2: Fundamental Relationship of Green Roofing's NPV

The cumulative NPV of green roofing is shown in the graph of Figure 3. From the graph, we can see that the policy enacted by Chicago did increase the NPV of green roofing, whereas the policies of San Francisco caused a decrease. The Toronto policy had no observed effect. The increase observed in the case of Chicago is explained by the $0.05 fee reduction per sq. ft. which was directly added to the benefit curve. The decrease in the San Francisco test case occurred because one building was mandated to cover its entire roof area with green roofing, which in turn forced this developer to install an amount of green roofing that had a negative NPV.

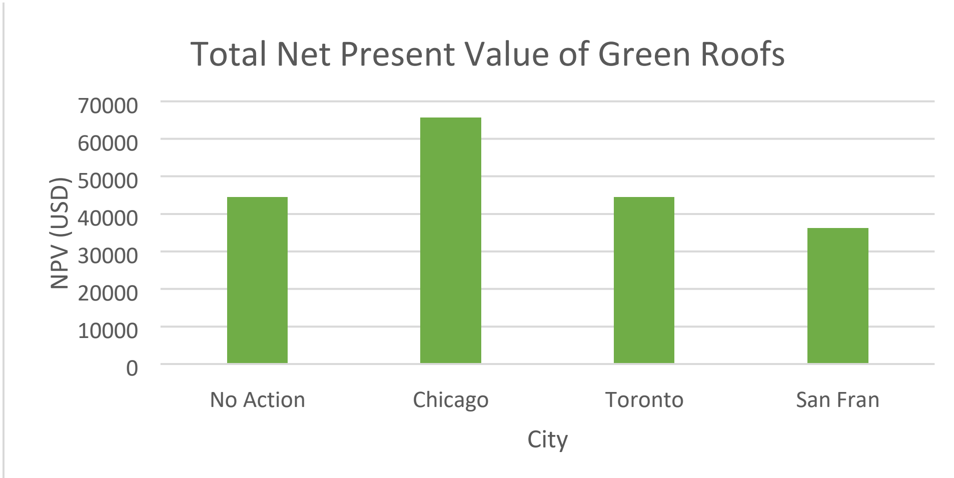


Figure 3: Graph displaying the aggregate NPV of Green Roofs of the sample

From Figure 4 we can see that even with the limited these policies have, there is an influence on the NPV of green roofing. This is especially notable in the case of the Chicago policy because the contribution of the fee reduction to the benefit curve aggregated over the roof area on average increased each roofs NPV by $10.56. From this, it is possible to determine that the average size of green roofing on a building is 211 sq. ft.

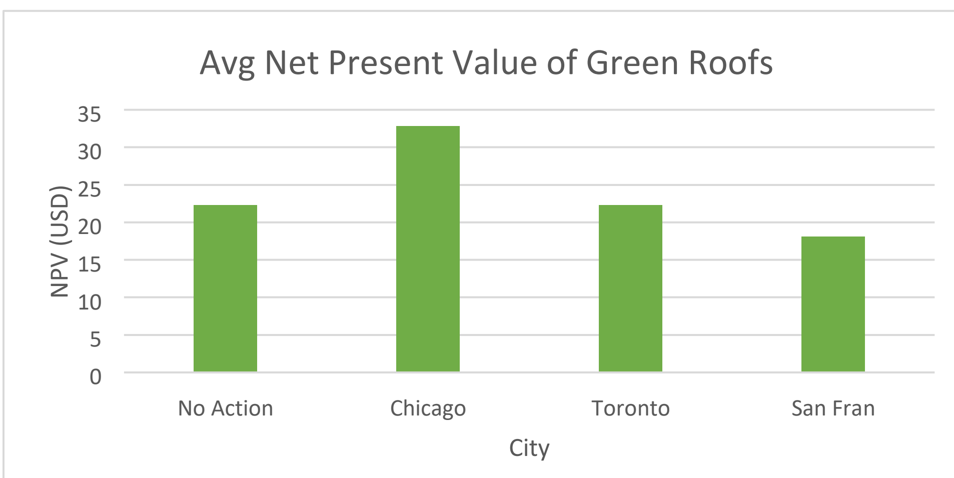


Figure 4: Graph displaying the average NPV of green roofing in the sample

The total area of green roofing was not strongly influenced by any of the policies as shown in Figure 5. In the cases of Toronto and Chicago, there was no increase. All buildings observed still abided by the 24% optimal coverage derived in the No Action model. (Note that the Chicago policy increased the optimal coverage to 25% when the fee reduction was increased to $0.50.) The San Francisco policy only had a small impact because only one developer was affected by the mandate, which forced them to install an excessive amount of green roofing for their economic situation.

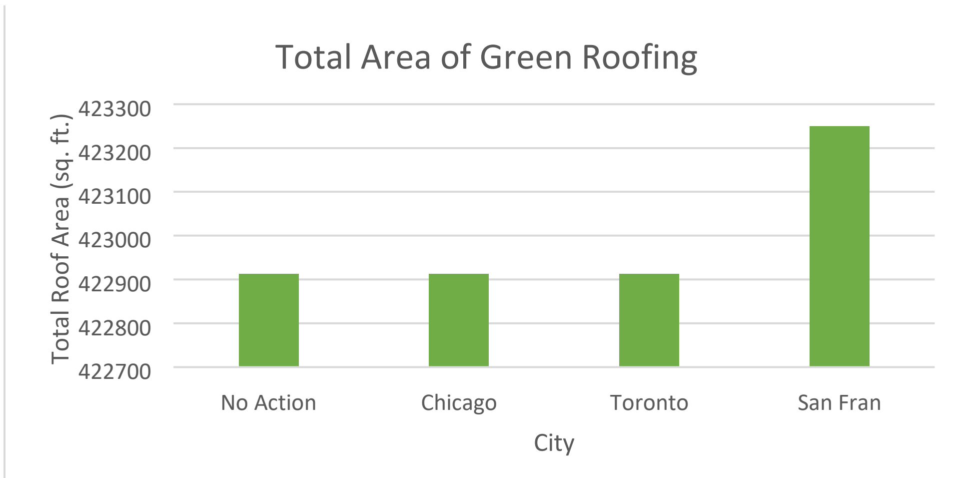


Figure 5: Graph displaying the total area of green roofing installed in the sample

Since the roofing in the Toronto and Chicago cases were not influenced by the policies, there is no difference in the cost of roof replacement at the 20-year mark. Only in the case of San Francisco, where again the mandated developer was forced to make their entire roof a green roof did this parameter change because in this case no replacement was needed, providing some benefit. This is shown in the graph of Figure 6.

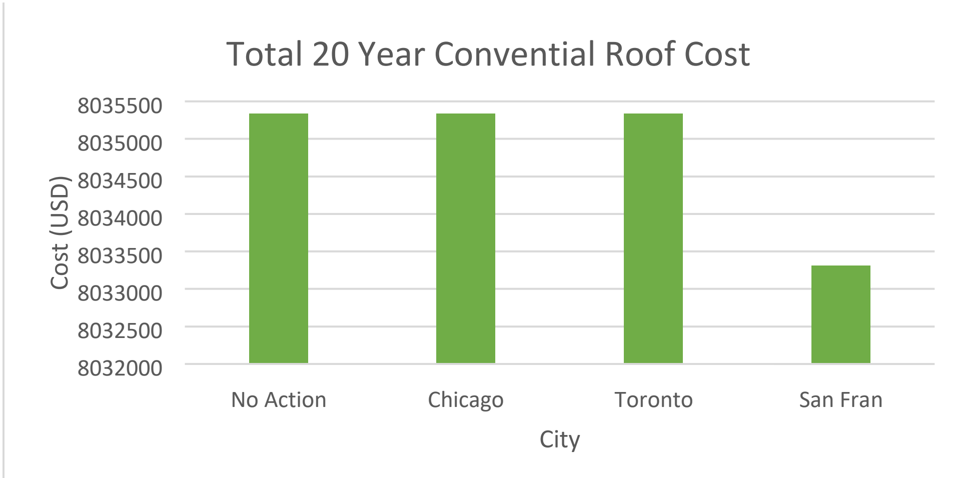


Figure 6: Graph displaying the aggregate cost of roof replacement at 20 years.

These results show that the policies in discussion have little impact on the behavior of green roof installation.

Discussion

The conclusions from these models is that these policies generally do not have much impact on the total area of roofing installed. The amount of green roofing in Chicago is virtually unaffected by the incentive since the $0.05 fee reduction per sq. ft. of green roofing does not contribute a meaningful incentive to install more green roofing. The policy could have some benefit in making green roofing better known and providing increases in NPV. Meanwhile, the mandates of San Francisco and Toronto carve out exceptions that in effect mean the mandates do not apply to most buildings, which in the simulation means almost all buildings behave according to the general economic model. If this had been tested on new development, this mandated would likely have been avoided if it meant installing an amount of green roofing with a negative NPV.

The general economic model does suggest that with the given economic parameters retrieved from governmental agencies, a 24% roof coverage is optimal. This does not mean that higher proportions of green roof coverage cannot return a benefit, but rather that the 24% mark has the greatest gap between the benefit and cost curves discussed in Figure 2. The model developed should be considered a first pass at this endeavor. To improve the development and analysis of this data the following should be considered:

- Size of roofs on per area basis (currently derived from other variables)
- Cost of green roof on a square foot basis in a local economy
- Average lifetime cycle of a green roof on a local scale

To consider if a roof is a good candidate for a retrofitting of a green roof the following could be considered:

- The rated load weights of buildings
- The per area weight of an extensive green roof
- If building needs to undergo renovation, would it justify making the building suitable for green roofing given its cost is justified within 1 green roof cycle.
- More precise annual maintenance costs of green roof on a per area basis in a local area.

(Or estimated green roof maintenance costs over life time on per area basis)

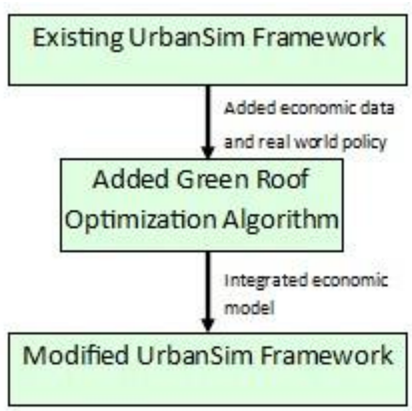
- Exact economy of scales of green roofing

The following are things to consider about UrbanSim:

- Computations assume NPV (salvage value assumed to be zero due to lack of information)

Future Work

The results reported and discussed in the previous section used already existing buildings to see how the policy would have affected them. There are some useful conclusions that one can draw from this analysis to help answer the project questions as well as provide more information for a hypothesis of how proposed development would behave. The integration frame work uses code from greenroof.py to run the desired optimization algorithm on each proposed building. The optimization algorithm will return a number that will be added (or subtracted) from the cost of the building. UrbanSim will then continue with its own optimization algorithms to select the arrangement of buildings that will give the developer the highest return for the specified parcel. If this integration is fully implemented, the conclusions drawn from this study can provide an even deeper insight into the effects of these policies.



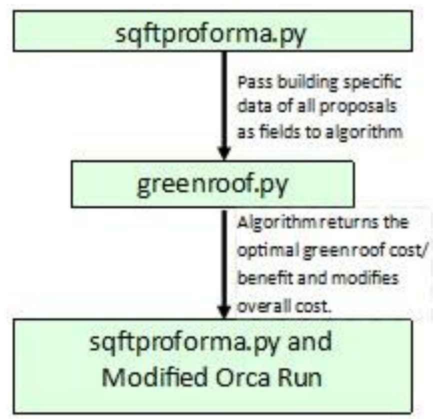


Figure 7: Integration framework

References

Atlanta City Council. (2003). *A Substitute Ordinance to Enact the City of Atlanta Sustainable Development Design Standards; to Promote Consistent Application of Sustainable Green Building Practice; Incorporate Sustainable Building Design and Construction Practices into City Financed Projects; and for Other Purposes.* Retrieved from: http://www.atlantaga.gov/Home/ShowDocument?id=547

Braham, A. (2017) *Fundamentals of Sustainability in Civil Engineering* (pp.59-63). Boca Raton, FL: CRC Press.

City of Chicago Department of Buildings. (2012). *Green Permit Process Flow Chart*. Retrieved from: https://www.cityofchicago.org/content/dam/city/depts/bldgs/general/GreenPermit/110112

Green_Permit_Flow_Chart.pdf

City of Chicago Department of Buildings (n.d.) *Green Permit Program Green Roof – Project Submittal Checklist*. Retrieved from: https://www.cityofchicago.org/content/dam/city/depts/bldgs/general/GreenPermit/Green_Roof_Checklistada.pdf

City of Chicago Department of Water Management. (n.d.) *Green Roofs: Best Management Practices*. Retrieved from: https://www.cityofchicago.org/city/en/depts/water/supp_info/conservation/green_design/green_roofs_bestmanagementpractices.html

City of Toronto Planning & Development. (n.d.) *Green Roof Bylaw*. Retrieved from: https://www1.toronto.ca/wps/portal/contentonly?vgnextoid=83520621f3161410VgnVCM10000071d60f89RCRD&vgnextchannel=3a7a036318061410VgnVCM10000071d60f89RCRD

Dunnett, N. & Kingsbury, N. (2008). *Planting Green Roofs and Living Walls* (2nd ed.). Portland, OR: Timber Press.

Green T. L., Kronenberg J., Andersson E., Elmqvist T., & Goméz-Baggethun, E. (2016). Insurance Value of Green Infrastructure in and Around Cities. *Ecosystems, 19*, 1051-1063. doi: 10.1007/s10021-016-9986-x

Lovell, S. T., & Taylor, J. R. (2013). *Supplying urban ecosystem services through multifunctional green infrastructure in the United States*. Retrieved from: https://www.researchgate.net/publication/257504191_Supplying_urban_ecosystem_services_through_multifunctional_green_infrastructure_in_the_United_States

Meadows, D. H. (2008). *Thinking in Systems*. White River Junction: Chelsea Green Publishing Company.

Meerow, S., & Newell, J. P. (2016). *Spatial planning for multifunctional green infrastructure: Growing resilience in Detroit*. Retrieved from: http://ac.elscdn.com/S0169204616302250/1-s2.0-S0169204616302250-main.pdf?_tid=4fa74e04-6199-11e7-98b8-00000aab0f02&acdnat=1499269855_058c339e2e677d688f4cf029a03ab27d

Prince George's County Department of the Environment. (n.d.) *Green Roof Fact Sheet*. Retrieved from: https://cbtrust.org/wp-content/uploads/Green-Roof_Fact-Sheet-and-Guidelines.pdf

United States Department of the Interior National Park Service. (n.d.) *Green Roof Benefits*. Retrieved from: https://www.nps.gov/tps/sustainability/new-technology/greenroofs/benefits.htm

United States Environmental Protection Agency. (2014). *Reducing Urban Heat Islands: Compendium of Strategies; Green Roofs*. Retrieved from: https://www.epa.gov/sites/production/files/2014-06/documents/greenroofscompendium.pdf

San Francisco Board of Supervisors. (2016). *Memorandum* [File No. 160154]. Retrieved from: https://sfenvironment.org/sites/default/files/events/proposed_better_roof_ordinance.pdf

San Francisco Planning Department. (2016). *San Francisco Living Roof Manual.* Retrieved from: https://issuu.com/sfplanningdepartmentlivingroofs/docs/san_francisco_living_roof_manual_we

Tennessee Department of Environment and Conservation & University of Tennessee (2014). *Tennessee Permanent Stormwater Management and Design Guidance Manual*.

(pp. 215-226). Retrieved from: https://app.box.com/s/pdl1afehg00s1wwqa94d8qmizyptxw3i/file/25367692645

The University of Pennsylvania, The Wharton School. (n.d.) *Economies of Scale*. Retrieved from: http://kwhs.wharton.upenn.edu/term/economies-of-scale/

The University of Washington, College of the Environment. (n.d.) *Mental Health and Function*. Retrieved from: https://depts.washington.edu/hhwb/Thm_Mental.html

UrbanSim Inc. (2017). UrbanSim [computer software]. Available as Python download[3].

Vargo, J., Stone B., Habeeb D., Liu P., & Russel A. (2016). The Social and Spatial Distribution of Temperature-Related Health Impacts from Urban Heat Island Reduction Policies. *Environmental Science & Policy, 66,* 366-374. http:dx.doi.org/10.1016/j.envsci.2016.08.012

Wadell, P. (2002). UrbanSim: Modeling Urban Development for Land Use, Transportation, and Environmental Planning. *Journal of the American Planning Association, 68*, 297-314. doi:10.1080/01944360208976274

Wilkinson, S. J., & Reed, R. (2009). Green roof retrofit potential in the central business district. *Property Management, 27* (5), 284-301. https://doi.org/10.1108/02637470910998456

United States General Services Administration (2011). *The Benefits and Challenges of Green Roofs on Public and Commercial Buildings.* Retrieved from: https://www.gsa.gov/portal/mediaId/158783/fileName/The_Benefits_and_Challenges_of_Green_Roofs_on_Public_and_Commercial_Buildings.action

Appendix A

Code for No Intervention Model:

```
############################
############################
#NO ACTION POLCIY TESTS
############################
############################

def NoInterventionGreenRoof():

    building_size_dict = {}
    roofins_dict = {}
    green_roof_ben_dict = {}
    green_roof_cost_dict = {}
    roof_cost_at_20yrs_dict = {}
    size_dict = {}
    best_NPV = 0
    index = building_id
        best_ben = 0
        building_size = (data['sq_ft'][index])/(data['stories'][index])
        roof_cost_at_20yrs = building_size * 6
        building_size_dict.update({index : building_size})

        for size_ratio in my_range (0, 1.01, .01):
            green_roof_cost = 23.907*(12**(-0.078)) *size_ratio * building_size +
(40*.02*building_size*size_ratio) + (building_size*size*ratio*.21)
            green_roof_ben = .23 * size_ratio * building_size * 40 + (building_size
* 6 * (1-size_ratio))
            if(green_roof_ben - green_roof_cost > best_ben):
                roof_ins = 1
                best_size = size_ratio * building_size
                size_dict.update({index : best_size})
                roofins_dict.update({index : roof_ins})
                green_roof_ben_dict.update({index : green_roof_ben})
                green_roof_cost_dict.update({index : green_roof_cost})
                roof_cost_at_20yrs = building_size * 6 * (1-size_ratio)
                roof_cost_at_20yrs_dict.update({index : roof_cost_at_20yrs})
                best_NPV = green_roof_ben = green_roof_cost
    greenbuildings = pd.DataFrame({"building size" : building_size_dict,
"best_size" : size_dict, "roofins" : roofins_dict, "green_ben" :
green_roof_ben_dict, "green_cost" : green_roof_cost_dict, "cost_20yr" :
roof_cost_at_20yrs_dict, })
    writer = pd.ExcelWriter('no_action.xlsx')
    buildings.to_excel(writer,'no_action')
    writer.save()
    #return best_NPV
```

Code for San Francisco Model:

```
############################
############################
#SAN FRAN STYLE POLCIY TESTS
############################
############################

def SanFranGreenRoof(self):
    building_size_dict = {}
    roofins_dict = {}
    green_roof_ben_dict = {}
    green_roof_cost_dict = {}
    roof_cost_at_20yrs_dict = {}
    size_dict = {}
    mandated_dict = {}
    for index in range(-1, 2000, 1):
        index = index + 1
        best_ben = 0
        building_size = (data['sq_ft'][index])/(data['stories'][index])
        roof_cost_at_20yrs = building_size * 6
        building_size_dict.update({index : building_size})

        #if(data['building_type_id'][index] != 'Residential' and building_size <
15625):
        if(building_type_id != 'Residential' and building_size < 15625):
            mandated_dict.update({index : 1})
            green_roof_cost = 23.907*(12**(-0.078)) *size_ratio * building_size +
(40*.02*building_size*size_ratio) + (building_size*size*ratio*.21)
            green_roof_ben = .23 * size_ratio * building_size * 40 + (building_size
* 6 * (1-size_ratio))
            roof_ins = 1
            best_size = building_size
            size_dict.update({index : 1})
            roofins_dict.update({index : roof_ins})
            green_roof_ben_dict.update({index : green_roof_ben})
            green_roof_cost_dict.update({index : green_roof_cost})
            roof_cost_at_20yrs_dict.update({index : 0})

        elif(data['building_type_id'][index] != 'Residential' and building_size >=
15625):
            mandated_dict.update({index : 1})
            green_roof_ben = .23 * size_ratio * building_size * 40 + (building_size
* 6 * (1-size_ratio))
            green_roof_cost = 23.907*(12**(-0.078)) *size_ratio * building_size +
(40*.02*building_size*size_ratio) +(building_size*size*ratio*.21)
            roof_ins = 1
            best_size = 15625
            size_dict.update({index : 1})
            roofins_dict.update({index : roof_ins})
            green_roof_ben_dict.update({index : green_roof_ben})
            green_roof_cost_dict.update({index : green_roof_cost})
            roof_cost_at_20yrs_dict.update({index : 0})

        else:
            mandated_dict.update({index : 0})
```

```
            for size_ratio in my_range (0, 1.01, .01):
            green_roof_cost = 23.907*(12**(-0.078)) *size_ratio * building_size +
(40*.02*building_size*size_ratio) + (building_size*size*ratio*.21)
            green_roof_ben = .23 * size_ratio * building_size * 40 + (building_size
* 6 * (1-size_ratio))
                if(green_roof_ben - green_roof_cost > best_ben):
                    roof_ins = 1
                    best_size = size_ratio * building_size
                    size_dict.update({index : best_size})
                    roofins_dict.update({index : roof_ins})
                    green_roof_ben_dict.update({index : green_roof_ben})
                    green_roof_cost_dict.update({index : green_roof_cost})
                    roof_cost_at_20yrs = building_size * 6 * (1-size_ratio)
                    roof_cost_at_20yrs_dict.update({index : roof_cost_at_20yrs})

    buildings = pd.DataFrame({"building size" : building_size_dict, "best_size" :
size_dict, "roofins" : roofins_dict, "green_ben" : green_roof_ben_dict,
"green_cost" : green_roof_cost_dict, "cost_20yr" : roof_cost_at_20yrs_dict,
"mandated" : mandated_dict})
    writer = pd.ExcelWriter('san_fran.xlsx')
    buildings.to_excel(writer,'san_fran')
    writer.save()
    return
```

Code for Toronto Policy:

```
############################
############################
#TORONTO STYLE POLCIY TESTS
############################
############################

def TorontoGreenRoof(self):
    building_size_dict = {}
    roofins_dict = {}
    green_roof_ben_dict = {}
    green_roof_cost_dict = {}
    roof_cost_at_20yrs_dict = {}
    size_dict = {}
    mandated_dict = {}
    green_roof_min_dict = {}
    for index in range(-1, 2000, 1):
        index = index + 1
        best_ben = 0
        building_size = (data['sq_ft'][index])/(data['stories'][index])
        roof_cost_at_20yrs = building_size * 6
        building_size_dict.update({index : building_size})
        if(data['building_type_id'][index] != 'Residential' or
((data['building_type_id'][index] == 'Residential' and data['stories'][index] >
6))):
            mandated_dict.update({index : 1})
            if(building_size > 21525 and building_size <= 53800):
                green_roof_min = .2
            elif(building_size > 53800 and building_size <= 107625):
                green_roof_min = .3
            elif(building_size > 107625 and building_size <= 161450):
```

```
                green_roof_min = .4
            elif(building_size > 161450 and building_size <= 215275):
                green_roof_min = .5
            elif (building_size > 215275):
                green_roof_min = .6
            else:
                green_roof_min = 0

            green_roof_min_dict.update( {index : green_roof_min})
            green_roof_cost = 23.907*(12**(-0.078)) * building_size +
(40*.02*building_size*green_roof_min)
            green_roof_ben = 1.23 * building_size * 40 + (building_size * 6 * (1-
green_roof_min))
            roof_ins = 1
            best_size = building_size * green_roof_min
            size_dict.update({index : 1})
            roofins_dict.update({index : roof_ins})
            green_roof_ben_dict.update({index : green_roof_ben})
            green_roof_cost_dict.update({index : green_roof_cost})
            roof_cost_at_20yrs_dict.update({index : 0})

            for size_ratio in my_range (green_roof_min, 1.01, .01):
                green_roof_cost = 23.907*(12**(-0.078)) *size_ratio * building_size
+ (40*.02*building_size*size_ratio)
                green_roof_ben = 1.23 * size_ratio * building_size * 40 +
(building_size * 6 * (1-size_ratio)) + (.05*size_ratio*building_size)
                if(green_roof_ben - green_roof_cost > best_ben):
                    roof_ins = 1
                    best_size = size_ratio * building_size
                    size_dict.update({index : best_size})
                    roofins_dict.update({index : roof_ins})
                    green_roof_ben_dict.update({index : green_roof_ben})
                    green_roof_cost_dict.update({index : green_roof_cost})
                    roof_cost_at_20yrs = building_size * 6 * (1-size_ratio)
                    roof_cost_at_20yrs_dict.update({index : roof_cost_at_20yrs})

        else:
            mandated_dict.update({index : 0})
            green_roof_min_dict.update( {index : 0})
            for size_ratio in my_range (0, 1.01, .01):
                green_roof_cost = 23.907*(12**(-0.078)) *size_ratio * building_size
+ (40*.02*building_size*size_ratio)
                green_roof_ben = 1.23 * size_ratio * building_size * 40 +
(building_size * 6 * (1-size_ratio)) + (.05*size_ratio*building_size)
                if(green_roof_ben - green_roof_cost > best_ben):
                    roof_ins = 1
                    best_size = size_ratio * building_size
                    size_dict.update({index : best_size})
                    roofins_dict.update({index : roof_ins})
                    green_roof_ben_dict.update({index : green_roof_ben})
                    green_roof_cost_dict.update({index : green_roof_cost})
                    roof_cost_at_20yrs = building_size * 6 * (1-size_ratio)
                    roof_cost_at_20yrs_dict.update({index : roof_cost_at_20yrs})

    buildings = pd.DataFrame({"building size" : building_size_dict, "best_size" :
size_dict, "roofins" : roofins_dict, "green_ben" : green_roof_ben_dict,
```

```
"green_cost" : green_roof_cost_dict, "cost_20yr" : roof_cost_at_20yrs_dict,
"mandated" : mandated_dict, "green_min" : green_roof_min_dict})
    writer = pd.ExcelWriter('toronto.xlsx')
    buildings.to_excel(writer,'toronto')
    writer.save()
    return
```

Code for Chicago Policy:

```
############################
############################
#CHICAGO STYLE POLCIY TESTS
############################
############################

def ChicagoGreenRoof():
    building_size_dict = {}
    roofins_dict = {}
    green_roof_ben_dict = {}
    green_roof_cost_dict = {}
    roof_cost_at_20yrs_dict = {}
    size_dict = {}
    for index in range(-1, 2000, 1):
        index = index + 1
        best_ben = 0
        building_size = (data['sq_ft'][index])/(data['stories'][index])
        roof_cost_at_20yrs = building_size * 6
        building_size_dict.update({index : building_size})
        for size_ratio in my_range (0, 1.01, .01):
            green_roof_cost = 23.907*(12**(-0.078)) *size_ratio * building_size +
(40*.02*building_size*size_ratio)
            green_roof_ben = 1.23 * size_ratio * building_size * 40 +
(building_size * 6 * (1-size_ratio)) + (.05*size_ratio*building_size)
            if(green_roof_ben - green_roof_cost > best_ben):
                roof_ins = 1
                best_size = size_ratio * building_size
                size_dict.update({index : best_size})
                roofins_dict.update({index : roof_ins})
                green_roof_ben_dict.update({index : green_roof_ben})
                green_roof_cost_dict.update({index : green_roof_cost})
                roof_cost_at_20yrs = building_size * 6 * (1-size_ratio)
                roof_cost_at_20yrs_dict.update({index : roof_cost_at_20yrs})

    buildings = pd.DataFrame({"building size" : building_size_dict, "best_size" :
size_dict, "roofins" : roofins_dict, "green_ben" : green_roof_ben_dict,
"green_cost" : green_roof_cost_dict, "cost_20yr" : roof_cost_at_20yrs_dict})
    writer = pd.ExcelWriter('chicago.xlsx')
    buildings.to_excel(writer,'chicago')
    writer.save()
```

Appendix B

Code from greenroof.py

```
import pandas as pd
data = pd.read_csv('data.csv')
##This is used to bound start and end of for loops
def my_range(start, end, step):
    while start <= end:
        yield start #keyword yield generates an interator
        start += step
        return


############################
############################
#NO ACTION POLCIY TESTS
############################
############################

def NoInterventionGreenRoof(self):

    building_size_dict = {}
    roofins_dict = {}
    green_roof_ben_dict = {}
    green_roof_cost_dict = {}
    roof_cost_at_20yrs_dict = {}
    size_dict = {}
    best_NPV = 0
    index = building_id
    best_ben = 0
    building_size = sq_ft/stories
    roof_cost_at_20yrs = building_size * 6
    building_size_dict.update({index : building_size})

    for size_ratio in my_range (0, 1.01, .01):
        green_roof_cost = 23.907*(12**(-0.078)) *size_ratio * building_size +
(40*.02*building_size*size_ratio) + (building_size*size*ratio*.21)
        green_roof_ben = .23 * size_ratio * building_size * 40 + (building_size * 6
* (1-size_ratio))
        if(green_roof_ben - green_roof_cost > best_ben):
             roof_ins = 1
             best_size = size_ratio * building_size
             size_dict.update({index : best_size})
             roofins_dict.update({index : roof_ins})
             green_roof_ben_dict.update({index : green_roof_ben})
             green_roof_cost_dict.update({index : green_roof_cost})
             roof_cost_at_20yrs = building_size * 6 * (1-size_ratio)
             roof_cost_at_20yrs_dict.update({index : roof_cost_at_20yrs})
             best_NPV = green_roof_ben - green_roof_cost
    greenbuildings = pd.DataFrame({"building size" : building_size_dict,
"best_size" : size_dict, "roofins" : roofins_dict, "green_ben" :
green_roof_ben_dict, "green_cost" : green_roof_cost_dict, "cost_20yr" :
roof_cost_at_20yrs_dict, })
    return best_NPV
```

```
############################
############################
#SAN FRAN STYLE POLCIY TESTS
############################
############################

def SanFranGreenRoof(self):
    building_size_dict = {}
    roofins_dict = {}
    green_roof_ben_dict = {}
    green_roof_cost_dict = {}
    roof_cost_at_20yrs_dict = {}
    size_dict = {}
    mandated_dict = {}
    index = building_id
    best_ben = 0
    building_size = (sq_ft/stories
    roof_cost_at_20yrs = building_size * 6
    building_size_dict.update({index : building_size})

    if(building_type_id != 'Residential' and building_size < 15625):
        mandated_dict.update({index : 1})
        green_roof_cost = 23.907*(12**(-0.078)) *size_ratio * building_size +
(40*.02*building_size*size_ratio) + (building_size*size*ratio*.21)
        green_roof_ben = .23 * size_ratio * building_size * 40 + (building_size * 6
* (1-size_ratio))
        roof_ins = 1
        best_size = building_size
        size_dict.update({index : 1})
        roofins_dict.update({index : roof_ins})
        green_roof_ben_dict.update({index : green_roof_ben})
        green_roof_cost_dict.update({index : green_roof_cost})
        roof_cost_at_20yrs_dict.update({index : 0})

        elif(building_type_id != 'Residential' and building_size >= 15625):
            mandated_dict.update({index : 1})
            green_roof_ben = .23 * size_ratio * building_size * 40 + (building_size
* 6 * (1-size_ratio))
            green_roof_cost = 23.907*(12**(-0.078)) *size_ratio * building_size +
(40*.02*building_size*size_ratio) +(building_size*size*ratio*.21)
            roof_ins = 1
            best_size = 15625
            size_dict.update({index : 1})
            roofins_dict.update({index : roof_ins})
            green_roof_ben_dict.update({index : green_roof_ben})
            green_roof_cost_dict.update({index : green_roof_cost})
            roof_cost_at_20yrs_dict.update({index : 0})
            best_NPV = green_roof_ben - green_roof_cost


        else:
            mandated_dict.update({index : 0})
            for size_ratio in my_range (0, 1.01, .01):
            green_roof_cost = 23.907*(12**(-0.078)) *size_ratio * building_size +
(40*.02*building_size*size_ratio) + (building_size*size*ratio*.21)
            green_roof_ben = .23 * size_ratio * building_size * 40 + (building_size
* 6 * (1-size_ratio))
```

```
                if(green_roof_ben - green_roof_cost > best_ben):
                    roof_ins = 1
                    best_size = size_ratio * building_size
                    size_dict.update({index : best_size})
                    roofins_dict.update({index : roof_ins})
                    green_roof_ben_dict.update({index : green_roof_ben})
                    green_roof_cost_dict.update({index : green_roof_cost})
                    roof_cost_at_20yrs = building_size * 6 * (1-size_ratio)
                    roof_cost_at_20yrs_dict.update({index : roof_cost_at_20yrs})
                    best_NPV = green_roof_ben - green_roof_cost


    buildings = pd.DataFrame({"building size" : building_size_dict, "best_size" :
size_dict, "roofins" : roofins_dict, "green_ben" : green_roof_ben_dict,
"green_cost" : green_roof_cost_dict, "cost_20yr" : roof_cost_at_20yrs_dict,
"mandated" : mandated_dict})
    return best_NPV


############################
############################
#TORONTO STYLE POLCIY TESTS
############################
############################

def TorontoGreenRoof(self):
    building_size_dict = {}
    roofins_dict = {}
    green_roof_ben_dict = {}
    green_roof_cost_dict = {}
    roof_cost_at_20yrs_dict = {}
    size_dict = {}
    mandated_dict = {}
    green_roof_min_dict = {}
    index = building_id
    building_size = sq_ft/stories
    roof_cost_at_20yrs = building_size * 6
    building_size_dict.update({index : building_size})
    if(building_type_id != 'Residential' or ((building_type_id == 'Residential' and
'stories' > 6))):
            mandated_dict.update({index : 1})
            if(building_size > 21525 and building_size <= 53800):
                green_roof_min = .2
            elif(building_size > 53800 and building_size <= 107625):
                green_roof_min = .3
            elif(building_size > 107625 and building_size <= 161450):
                green_roof_min = .4
            elif(building_size > 161450 and building_size <= 215275):
                green_roof_min = .5
            elif (building_size > 215275):
                green_roof_min = .6
            else:
                green_roof_min = 0

            green_roof_min_dict.update( {index : green_roof_min})
            green_roof_cost = 23.907*(12**(-0.078)) * building_size +
(40*.02*building_size*green_roof_min)
```

```
            green_roof_ben = 1.23 * building_size * 40 + (building_size * 6 * (1-
green_roof_min))
            roof_ins = 1
            best_size = building_size * green_roof_min
            size_dict.update({index : 1})
            roofins_dict.update({index : roof_ins})
            green_roof_ben_dict.update({index : green_roof_ben})
            green_roof_cost_dict.update({index : green_roof_cost})
            roof_cost_at_20yrs_dict.update({index : 0})

            for size_ratio in my_range (green_roof_min, 1.01, .01):
                green_roof_cost = 23.907*(12**(-0.078)) *size_ratio * building_size
+ (40*.02*building_size*size_ratio)
                green_roof_ben = 1.23 * size_ratio * building_size * 40 +
(building_size * 6 * (1-size_ratio)) + (.05*size_ratio*building_size)
                if(green_roof_ben - green_roof_cost > best_ben):
                    roof_ins = 1
                    best_size = size_ratio * building_size
                    size_dict.update({index : best_size})
                    roofins_dict.update({index : roof_ins})
                    green_roof_ben_dict.update({index : green_roof_ben})
                    green_roof_cost_dict.update({index : green_roof_cost})
                    roof_cost_at_20yrs = building_size * 6 * (1-size_ratio)
                    roof_cost_at_20yrs_dict.update({index : roof_cost_at_20yrs})

        else:
            mandated_dict.update({index : 0})
            green_roof_min_dict.update( {index : 0})
            for size_ratio in my_range (0, 1.01, .01):
                green_roof_cost = 23.907*(12**(-0.078)) *size_ratio * building_size
+ (40*.02*building_size*size_ratio)
                green_roof_ben = 1.23 * size_ratio * building_size * 40 +
(building_size * 6 * (1-size_ratio)) + (.05*size_ratio*building_size)
                if(green_roof_ben - green_roof_cost > best_ben):
                    roof_ins = 1
                    best_size = size_ratio * building_size
                    size_dict.update({index : best_size})
                    roofins_dict.update({index : roof_ins})
                    green_roof_ben_dict.update({index : green_roof_ben})
                    green_roof_cost_dict.update({index : green_roof_cost})
                    roof_cost_at_20yrs = building_size * 6 * (1-size_ratio)
                    roof_cost_at_20yrs_dict.update({index : roof_cost_at_20yrs})
                    best_NPV = green_roof_ben - green_roof_cost


    buildings = pd.DataFrame({"building size" : building_size_dict, "best_size" :
size_dict, "roofins" : roofins_dict, "green_ben" : green_roof_ben_dict,
"green_cost" : green_roof_cost_dict, "cost_20yr" : roof_cost_at_20yrs_dict,
"mandated" : mandated_dict, "green_min" : green_roof_min_dict})
    return best_NPV

############################
############################
#CHICAGO STYLE POLCIY TESTS
############################
############################
```

```
def ChicagoGreenRoof(self):
    building_size_dict = {}
    roofins_dict = {}
    green_roof_ben_dict = {}
    green_roof_cost_dict = {}
    roof_cost_at_20yrs_dict = {}
    size_dict = {}
        best_ben = 0
        building_size = (sq_ft/stories)
        roof_cost_at_20yrs = building_size * 6
        building_size_dict.update({index : building_size})
        for size_ratio in my_range (0, 1.01, .01):
            green_roof_cost = 23.907*(12**(-0.078)) *size_ratio * building_size +
        (40*.02*building_size*size_ratio)
            green_roof_ben = 1.23 * size_ratio * building_size * 40 +
        (building_size * 6 * (1-size_ratio)) + (.05*size_ratio*building_size)
            if(green_roof_ben - green_roof_cost > best_ben):
                roof_ins = 1
                best_size = size_ratio * building_size
                size_dict.update({index : best_size})
                roofins_dict.update({index : roof_ins})
                green_roof_ben_dict.update({index : green_roof_ben})
                green_roof_cost_dict.update({index : green_roof_cost})
                roof_cost_at_20yrs = building_size * 6 * (1-size_ratio)
                roof_cost_at_20yrs_dict.update({index : roof_cost_at_20yrs}
        best_NPV = green_roof_ben - green_roof_cost

    buildings = pd.DataFrame({"building size" : building_size_dict, "best_size" :
size_dict, "roofins" : roofins_dict, "green_ben" : green_roof_ben_dict,
"green_cost" : green_roof_cost_dict, "cost_20yr" : roof_cost_at_20yrs_dict})
    return best_NPV
```

Appendix C

Relevant code from sqftproforma.py

```
    def _building_cost(self, use_mix, stories):
        """
        Generate building cost for a set of buildings

        Parameters
----------         use_mix
: array
            The mix of uses for this form
stories : series
            A Pandas Series of stories

        Returns
-------        array
            The cost per sqft for this unit mix and height.

        """
c = self.config
         heights = stories * c.height_per_story # stories to heights
costs = np.searchsorted(c.heights_for_costs, heights) # cost index for
this height

        costs[np.isnan(heights)] = 0 # this will get set to nan later

        costs = np.dot(np.squeeze(c.costs[costs.astype('int32')]), use_mix) #
compute cost with matrix multiply   #No Action green economy added
        costs = np.dot(np.squeeze(c.costs[costs.astype('int32')]), use_mix) -
             c.NoInterventionGreenRoof() #greenroof economy added
#Chicago style green roof economy added
        costs = np.dot(np.squeeze(c.costs[costs.astype('int32')]), use_mix) -
             c.ChicagoGreenRoof()

        #Toronto style green roof economy added
        costs = np.dot(np.squeeze(c.costs[costs.astype('int32')]), use_mix) -
             c.TorontoGreenRoof() #greenroof economy added

        #San Fran style green roof economy added
        costs = np.dot(np.squeeze(c.costs[costs.astype('int32')]), use_mix) -
             c.SanFranGreenRoof() #greenroof economy added

        # some heights aren't allowed - cost should be nan
costs[np.isnan(stories).flatten()] = np.nan
return costs.flatten()


        df['greendata'] = greenbuildings #defines green roof variables


outdf = pd.DataFrame({
            'building_sqft': twod_get(maxprofitind, building_bulks),
```

```
            'building_cost': twod_get(maxprofitind, building_costs),
            'parking_ratio': parking_sqft_ratio[maxprofitind].flatten(),
'stories': twod_get(maxprofitind, heights) / c.height_per_story,
            'total_cost': twod_get(maxprofitind, total_costs),
            'building_revenue': twod_get(maxprofitind, building_revenue),
            'max_profit_far': twod_get(maxprofitind, fars),
'max_profit': twod_get(maxprofitind, profit),
            'parking_config': parking_config
            'greendata': greenbuildings #adds green roof data to output
        }, index=df.index)
```