Integer Programming for Land Use Optimization in Urban Planning and Other Applications

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1 Introduction

The advent of more advanced methods in environmental analysis has brought with it a new understanding of the impacts and contributions urban areas can have on future ecosystems. One such method is the application of integer programming and mathematical optimization techniques to ecological and economic thinking. The intersection of these disciplines not only shows the difficult and dynamic nature of solutions, but also the vast array of applications. Future land development in the face of a changing climate is a well researched topic and presents a unique challenge. Using integer programming and variable optimization to help guide current decision making can help define the path forward to ensure continued viability and ecosystem health.

2 Applications outside of urban planning

Integer programming can be applied to a vast array of problems across multiple disciplines with relative ease. The documentation of such instances is well know and published frequently. Although most applications are iterative and mathematical in nature, the methods can still be applied to non-mathematical fields. Optimizing scheduling for a mental health clinic based on time allotments, daily constraints like personnel and exam rooms, and patient costs is easily done. Allocating rooms based on space and student size inside of an older school with an array of classroom sizes boils down to a simple optimization problem. The following are a diverse collection of interesting models using integer programming to solve complex tasks.

3.1 The marshalling problem

This application is based on *minimizing* the berthing time that cargo ships spend loading and unloading freight containers. Berthing time is the time a cargo ship spends docked at a terminal, and is seen as one of the most costly parts of terminal operations. In recent decades, the industry has been moving towards larger ships and shorter berthing times in order to *maximize* the return on shipping costs.[1] In addition, 80% of freight world wide is being carried by sea, showing a significant increase in throughput over even ten years ago. The added international trade agreements have driven a large portion of this, given that air freight is still more expensive than shipping. This puts a large strain on freight terminals, who are struggling to keep up with the demand. The author notes that increasing the size of the terminal is not always an available method for increasing output, however, optimizing existing space is.

A storage yard is the staging area for the freight terminal, where all soon-to-be loaded freight containers live. This staging area is the real bottleneck for terminals, and it's optimized storage is the key to this study. Inside the storage yard are bays which each house a certain number of stacks, each with a set height. Generally speaking, containers are offloaded and put into these bays based on which ship they're about to be loaded on. It does not make sense to optimize storage at this point, because quickly unloading a ship is imperative to the time constraint. This

[1] Consuelo Parreño-Torres, Ramon Alvarez-Valdes, and Rubén Ruiz. "Integer programming models for the pre-marshalling problem". In: *European Journal of Operational Research* 274.1 (2019), pp. 142–154.

is the *pre-marshalling* stage. It makes far more sense to load them randomly into bays, and then to optimize storage based on which containers will need to be loaded onto the next ship first. Generally speaking, the lightest containers are *offloaded* first, while the heaviest containers are *loaded* first. Therefore, there's an order the containers in a bay must live in.

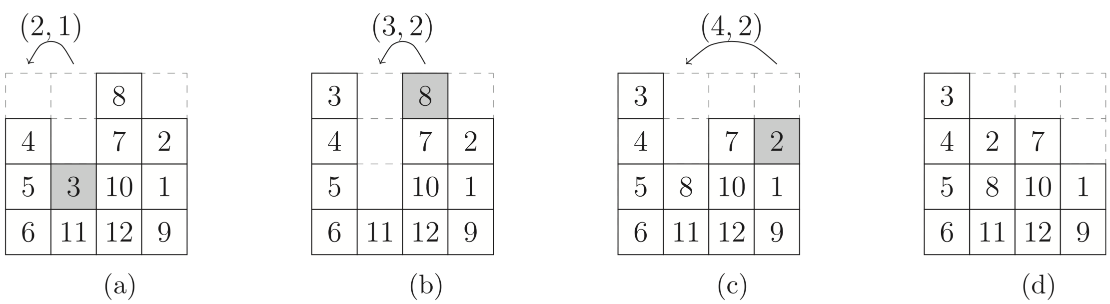


Fig. 1. Example solution to the pre-marshalling problem.[2]

To optimize storage, the researcher assigns a number to each container like in Fig. 1, and finds a solution that *minimizes* the number of configuration moves required of the forklift operator in order to allow the crane to access all the containers. In the above randomly selected example, the optimal solution involved three moves, which reduces the amount of time a crane operator would have to spend loading a ship. All variables, like time, are discrete and so this is purely an integer programming model. As a note, the researchers found that their model reduced berthing times over traditional methods, and helped optimize the process.

[2] Parreño-Torres, Alvarez-Valdes, and Ruiz, "Integer programming models for the pre-marshalling problem".

The bunker fuel used by cargo ships is inefficient and detrimental to ocean ecosystems.[3] A freighter can use between 150 and 300 tonnes of this fuel per day.[4] Limiting the amount of time spent idling at a freight terminal is a realistic way to reduce ocean pollution from this fuel sources. By optimizing the loading/unloading process, it's possible to achieve to a reduction in fuel - and by extension, expenditure on fuel - while also maximizing traffic - in order to maximize revenue for the terminal - and minimize waste. The economic achievements are profound at the individual and global scale, given the rates at which cargo are transported by sea. This type of application realizes significant benefits to global trade and marine ecosystems.

3.2 Geometric optimization for firefighters

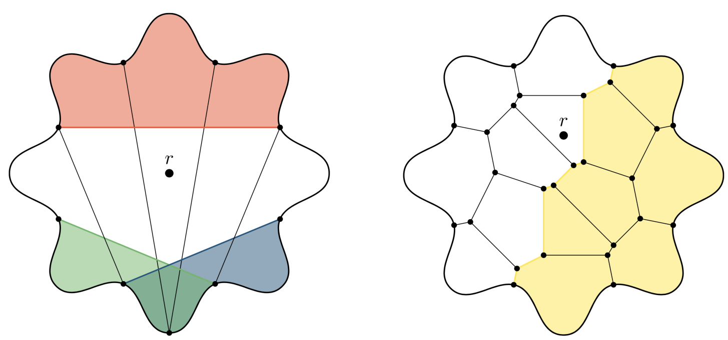
Another application of these methods is for optimizing barrier location and size for fighting wildfires. Obviously, fire is a natural occurrence, and is required for sustaining ecosystems and their services. However, suppose a fire was threatening a whole town, and that a fire department was tasked with protecting that town. Consider some polygon of finite area, and let some point inside the polygon be the origin of a fire. Given the location of the starting point of the fire, is it possible to *minimize* the burned area by using integer programming methodology?

The *Geometric Firefighter Problem* (GFP) tasks an individual with finding all possible combinations of potential land loss, and then minimize it given it linear

[3] Mauricio JO Zambon, Pedro J de Rezende, and Cid C de Souza. "Solving the geometric firefighter routing problem via integer programming". In: *European Journal of Operational Research* 274.3 (2019), pp. 1090–1101.

[4] *How Much Oil Is on That Ship.* URL: `https://response.restoration.noaa.gov/about/media/how-much-oil-ship.html`.

parameters. Suppose fire barriers can be constructed (singularly) but only between boundary points of the polygon, like in Fig. 2 (a). This represents a linearity constraint that most integer programming methodology imposes. Part (b) of Fig. 2 is the result of dropping the linearity constraint. So, assume we have barriers, all of which are the same discrete size, that can be constructed (singularly) in any form. This means you may be able to block off a larger portion of the town you were tasked to protect. This is called the *Geometric Firefighter Routing Problem* (GFRP).



(a) (b)

Fig. 2. Examples of different barrier sets.[5]

This type of model relies on particular abstract concepts from graph theory, but represents a very interesting application of integer programming into economic incentives (reducing fire risk, minimizing damage, reducing cost, etc.) and environmental quality (limiting particulate matter, reducing impact on protected areas, ensuring biodiversity in vulnerable regions, etc.). This type of problem lies outside the focus of this paper, but also lends itself to considerations for urban planning. Suppose you

[5] Zambon, Rezende, and Souza, "Solving the geometric firefighter routing problem via integer programming".

knew that some areas were more susceptible than others. Then you may be able to determine the quickest path of a fire from any starting point given the immediate surroundings. A city planner could mitigate risk by encouraging urban growth away form one region and towards another. Perhaps factoring in the distance of firefighters to some starting point of a fire shows a need for additional fire departments in a city as urban boundaries expand. This type of model may be used to predict such instances, and is therefore beneficial to consider.

3.3 Optimal satellite collection schedules

The process of optimizing satellite positions and their relative collection schedules also utilizes integer programming techniques. The demand for satellite imaging is increasing, and while the cost of deploying and operating remote sensing technology is declining, it is still sufficiently high to deter some firms from investing in their own deployments.[6] Some firms have made it their business to sell time on their own satellites, however they face many constraints given the growing demand. An optimal business application then would be to minimize time spent by each satellite on individual jobs, thus *maximizing* the number of jobs each satellite can perform over some time constraint.

Generally speaking, when a firm is trying to decide which projects are going to be accepted, they look at all the variables involved, not just time. For example, the number of satellites, the distance each one would have to travel, and the type

[6] Christopher G Valicka et al. "Mixed-integer programming models for optimal constellation scheduling given cloud cover uncertainty". In: *European Journal of Operational Research* 275.2 (2019), pp. 431–445.

of camera on the satellite are all considered. Any resulting schedule has to account for the utility from each scheduled collection and all possible constraints on when, where, and how each instance will be recorded and delivered. The goal of this model is to *minimize* the time it takes for each collection to occur. Additionally, there are multiple variants of integer programming that can be used.

Mixed-integer linear programming is required when thinking of time as a continuous variable, as is generally required for this type of model. However, bound calculations can be taxing on systems using the model. A more simple time-indexing could be introduced to discretize the time variable and turn the problem into a integer linear programming model. This formulation allows for better approximation of boundary values, and the researchers note that it offers many other benefits. Things like distance form target, time to commute, and others can also be discretized in this way. Then the optimal solution is one that *minimizes* the time of each instance. Being able to create efficient uses for satellite imaging has proved useful in firefighting[7] [8], ecosystem services mapping[9] [10], biodiversity monitoring[11] [12], and many others.

[7] *New Satellite Mapping Technique Gives Firefighters Big Picture*. URL: `https://www.fs.usda.gov/news/releases/new-satellite-mapping-technique-gives-firefighters-big-picture`.

[8] Jennifer Fadoul. *NASA Tracks Wildfires From Above to Aid Firefighters Below*. July 2019. URL: `https://www.nasa.gov/feature/goddard/2019/nasa-tracks-wildfires-from-above-to-aid-firefighters-below`.

[9] Xiaoming Feng et al. "Remote sensing of ecosystem services: An opportunity for spatially explicit assessment". In: *Chinese Geographical Science* 20.6 (2010), pp. 522–535.

[10] Carlos Ramirez-Reyes et al. "Reimagining the potential of Earth observations for ecosystem service assessments". In: *Science of the Total Environment* 665.C (2019).

[11] Sandra Luque et al. "Improving biodiversity monitoring using satellite remote sensing to provide solutions towards the 2020 conservation targets". In: *Methods Ecol Evol* 111 (2018), pp. 07030–5774.

[12] Harini Nagendra and Duccio Rocchini. "High resolution satellite imagery for tropical biodiversity studies: the devil is in the detail". In: *Biodiversity and conservation* 17.14 (2008), p. 3431.

3.4 Other applications

The previous uses of integer programming techniques are interesting in that they prove the wide array of applications. They also show that when you strip away the individual details, they're all attempting to optimize an economic or environmental variable of interest. Suppose you wanted to optimize both, and were tasked with allocating a budget to land management for conservation efforts. Specific spatial attributes of land could be used to develop a model to optimize biodiversity, ecosystem services, or budget limitations over time. For example, reserve proximity, connectivity, compactness, core, and buffer areas could be thought of as spatial design variables.[13] Non-spatial components could also be considered. For example, the maximum species covering problem[14] [15], or the dynamic reserve selection with uncertain site availability[16] [17].

The objective for each model involves *minimizing* land allocation and budget, or *maximizing* ecosystem services and biodiversity. The protection of one of the attributes leads to the protection of another, given the interplay of all systems. Fac-

[13] Robert G Haight and Stephanie A Snyder. "Integer programming methods for reserve selection and design". In: *In: Moilanen, Atte; Wilson, Kerrie A.; Possingham, Hugh, eds. Spatial conservation prioritization. Quantitative methods and computational tools. Oxford, UK: Oxford University Press: 43-57. Chapter 4.* (2009), pp. 43–57.

[14] Richard L Church, David M Stoms, and Frank W Davis. "Reserve selection as a maximal covering location problem". In: *Biological conservation* 76.2 (1996), pp. 105–112.

[15] Sahan TM Dissanayake et al. "Optimal selection of clustered conservation lands using integer programming: the case of Fort Stewart in Georgia, USA". in: *Handbook on the Economics of Ecosystem Services and Biodiversity.* Edward Elgar Publishing, 2014.

[16] Stephanie A Snyder, Robert G Haight, and Charles S ReVelle. "A scenario optimization model for dynamic reserve site selection". In: *Environmental Modeling & Assessment* 9.3 (2005), pp. 179–187.

[17] Christopher Costello and Stephen Polasky. "Dynamic reserve site selection". In: *Resource and Energy Economics* 26.2 (2004), pp. 157–174.

toring in the interactions between them is beyond the scope of any simple integer programming method, and involves more advanced stochastic processes.

3 Green infrastructure and urban planning

4.1 Urban stormwater management

The importance of stormwater management strategies is important for any city, but Portland in particular (given increased rainfall and difficulty with urban flooding) is especially concerned with offsetting these negative effects. In addition, given the proximity of Portland to the Willamette, and the number of endangered species that reside there, the effect of urban pollution in this specific ecosystem is of particular importance. Portland receives about 37 inches of rain per year.[18] Normally, soil and plants will use rain water in a positive way for ecological services. In urban areas, storm water will wash pollutants, dirt, and oil into water treatment centers that treat water for population consumption, and into our rivers. The storm water effectively moves urban pollutants into our water supply and local streams. In the city, we have *point* and *non-point* sources. Contaminants from the urban environment may be seen originally as a point source, but given our distance to the Willamette, these are actually non-point sources.[19] When our water supply is adversely affected by storm water, greater filtration is needed, representing an adverse economic impact. When storm water carries pollutants into our local streams, rivers, etc., it worsens aquatic ecosystems. Furthermore, when aquatic ecosystems are harmed, the surrounding

[18] City Club of Portland. *Invisible Enemies: Reducing Air Toxics in the Portland Airshed.* 2013.
[19] Thomas H Tietenberg and Lynne Lewis. *Environmental and natural resource economics.* Routledge, 2016.

ecosystems suffer.[20] It may, however, be possible to correct this added waste water burden by incorporating green infrastructure, housing method incentives, community support advocates, and other programs.

The *Water Pollution Control Act* of 1948 was really the first inkling of advocating for better water quality in urban areas. Later on, *The Clean Water Act* amendments in 1987 gave the responsibility of non-point source pollution control to individual states. Various other legislature have better defined these responsibilities, but urban storm water runoff is largely from an array of non-point sources. Portland has invested $1.4 billion in physical infrastructure projects in order to reduce combined sewer overflows (CSO). A combined sewer is a sewage collection system of pipes and tunnels designed to simultaneously collect surface runoff and sewage water in a shared system. So, a CSO is when the system is pushed past capacity, and triggers urban flooding. In 2008, Portland made another investment in the "Grey to Green" program to control stormwater runoff and combat the negative effects. Portland has a long history of investment in green infrastructure, and so the intersect of stormwater management practices and green infrastructure is well documented. Increased stormwater runoff puts strain on an already strained water management system. Sewer overflows have negative effects on immediate and surrounding habitats, and can alter the biodiversity of these areas. By extension, the potential for loss of ecosystem services increases with more urban pollution.[21] Being able to monitor and solve this problem effectively is an effective use of integer programming method-

[20]Lizhu Wang et al. "Impacts of urbanization on stream habitat and fish across multiple spatial scales". In: *Environmental management* 28.2 (2001), pp. 255–266.

[21]Ana E Barbosa, Joao N Fernandes, and Luis M David. "Key issues for sustainable urban stormwater management". In: *Water research* 46.20 (2012), pp. 6787–6798.

ology.

A variety of management practices, like green infrastructure, exist to combat environmental degradation associated with the altered hydrology of urban areas. Urbanization and the increase in impervious surfaces has been shown to result in a degraded water ecosystem.[22] *Green Roofs* are emerging as one of the potential solutions to stormwater runoff. As mentioned previously, reducing nonporous surfaces allows the local environment to provide additional stormwater storage. Green roofs are a collection of vegetation on top of a waterproof membrane that help retain water and balance the negative effects of urbanization on urban hydrology. It has been shown that they are effective in this task, as well as providing water pollution control.[23] In 2006, a group of researchers found that they were able to use spatial analysis to determine the overall portion of land cover that is an impervious surface.[24] From there, they were able to find the portion of total land cover that had a roof. The authors hypothesized that you would be able to use this information to develop green roof minimum area policy, which is somewhat similar to maximum impervious surface legislature. Urban areas would then have another tool to combat the problem. In addition, there are numerous other ecosystem services associated with more green space in urban environments, such as air quality control. If we were able to combine price hedonics with green roofs, we may be able to put a value on the effect of these green infrastructure schemes on total home price.

[22] Robert J Miltner, Dale White, and Chris Yoder. "The biotic integrity of streams in urban and suburbanizing landscapes". In: *Landscape and urban planning* 69.1 (2004), pp. 87–100.

[23] Timothy L Carter and Todd C Rasmussen. "Hydrologic behavior of vegetated roofs 1". In: *JAWRA Journal of the American Water Resources Association* 42.5 (2006), pp. 1261–1274.

[24] Timothy Carter and C Rhett Jackson. "Vegetated roofs for stormwater management at multiple spatial scales". In: *Landscape and urban planning* 80.1-2 (2007), pp. 84–94.

By using integer programming, it's possible to determine a *minimal* covering problem for green roof requirements. It's also possible to then discern the added benefit to a property or building that uses a green roof, and by extension a willingness to pay metric. A natural extension of this analysis would be to think about ecosystem service consolidation *above* urban areas, on rooftops and sides of buildings. From this point of view, one could use an integer programming method to accomplish any of the goals listed in Section 3.4. The advent of green roofs provides a new way to accomplish these goals. Another route of analysis may be the interaction between ground-level and roof ecosystems. An IP model would be able to *minimize* or *maximize* any number of attributes, including land use and space. Urban design could take into account needed green space *above* the city and could help develop new market incentives for building practices. The interaction of ecosystem services between green roofs spatially is not thoroughly explored, however some headway has been made which aims to optimize pollinator resources.[25]

4.2 Limiting urban sprawl

The share of total population living in urban areas has risen dramatically in recent years, and will continue to do so as populations grow.[26] Population density has also grown almost 2000% since 1970.[27] In addition, urban areas are forecasted

[25]Johannes Langemeyer et al. "Creating urban green infrastructure where it is needed–A spatial ecosystem service-based decision analysis of green roofs in Barcelona". In: *Science of the Total Environment* 707 (2020), p. 135487.

[26]H. Plecher. *United States - Urbanization 2018*. Feb. 2020. URL: `https://www.statista.com/statistics/269967/urbanization-in-the-united-states/`.

[27]Erin Duffin. *Population density of the United States 2019*. Feb. 2020. URL: `https://www.statista.com/statistics/183475/united-states-population-density/`.

to expand over the next few decades, with total area projected to increase by 79%.[28] Sprawl has an observed negative effect on immediate ecosystems and quality of life, and so requires careful management and precise attention. The Roman empire considered urban planning on a set of attributes that maximized military effect, limited travel to sectors of the city, provided merchant area, among others. From this and other developing nations in the ancient world, a pattern was established that is in its current form. Consider a set of four distinct *layers* to designing an urban expanse: the *physical base*, *political base*, *economic base*, and *social base*.[29]

The physical base involves parks, roads, and buildings. The political layer involves surrounding vital assets, more common in older civilizations. An economic layer looks at things like marketplaces and other commerce. Finally, the social base allows residents a place to socialize and gather. Since there are conflicting layers in city design, decision making processes have evolved to help city planners make models under any number of criteria. All of these layers involve spatial considerations that could be optimized using integer programming methods. This is an example of *maximizing* density with a minimal land use, in order to optimize city services in an urban framework.

4.3 Urban energy design

An optimization problem that relies on spatial data like urban density could be

[28] Ralph J Alig, Jeffrey D Kline, and Mark Lichtenstein. "Urbanization on the US landscape: looking ahead in the 21st century". In: *Landscape and urban planning* 69.2-3 (2004), pp. 219–234.

[29] Piyush Kumar, Jay M Rosenberger, and Gazi Md Daud Iqbal. "Mixed integer linear programming approaches for land use planning that limit urban sprawl". In: *Computers & Industrial Engineering* 102 (2016), pp. 33–43.

formulated under the integer programming framework, as previously noted.[30][31] As urban landscapes become more and more dense, the energy needs of the community will differentiate. Cities are major energy consumers and use about 67% of global primary demand and are responsible for about 71% of energy related green house gas emissions.[32] A number of factors affect energy needs like line-loss across distance. Voltage drops over distance, requiring whatever substation to increase the total energy transmitted. However, a higher urban density does not necessarily decrease power needs. As density rises, some building related energy needs will increase like vertical transport, air-conditioning, lighting, etc.[33] In addition, the density of the built environment has a significant impact on the urban climate.

The *urban heat effect* is motivated by urban density and lack of ecosystem services. Warming increases demand for other services like temperature control and the added energy cost counters the assumption that density rates are proportional to energy use rates. In effect, it may be possible to increase energy demand while trying to optimize distance for urban expansion. Applying integer programming to this scenario would *minimize* energy use, while *maximizing* the density of the urban sprawl in order to *minimize* land use. Another proposed method would be to use mixed-integer programming to better simulate real world demand.[34] This would al-

[30] Haight and Snyder, "Integer programming methods for reserve selection and design".

[31] Zambon, Rezende, and Souza, "Solving the geometric firefighter routing problem via integer programming".

[32] James Keirstead and Nilay Shah. "Calculating minimum energy urban layouts with mathematical programming and Monte Carlo analysis techniques". In: *Computers, Environment and Urban Systems* 35.5 (2011), pp. 368–377.

[33] Keirstead and Shah, "Calculating minimum energy urban layouts with mathematical programming and Monte Carlo analysis techniques".

[34] Sheila Samsatli and Nouri J Samsatli. "A general mixed integer linear programming model for the design and operation of integrated urban energy systems". In: *Journal of Cleaner Production*

low us to observe changes in energy demands given varying kinds of fuel.

4.4 Price hedonics as an optimization problem

The main subtopic of green infrastructure explored in this paper is the idea of a "green street". A green street is a stormwater management approach that incorporates vegetation, soil, and engineered systems to affect and limit the rates of stormwater runoff from impervious surfaces. Green streets are designed to capture rainwater at its source, where rain falls. Whereas, a traditional street is designed to direct stormwater runoff from impervious surfaces into storm sewer systems. If we are able to discern the affect of housing prices, it's possible to increase funding for green street projects, and take advantage of a positive externality on the local community.

Price hedonics methods allow us to measure how much something is worth given its relative impact on housing pricing.[35] A recent study was conducted in Portland to determine if *green streets* had a positive effect on housing prices.[36] After considering all variables, a two-year time span, and thousands of homes, the researchers were able to conclude that proximity to green infrastructure increased home prices. Using this effect to fund green infrastructure aimed at stormwater management practices is then viable. If housing prices increase with green infrastructure implementation, then the city could impose a portion of these costs on home owners who stand to gain

191 (2018), pp. 458–479.

[35] David Harrison Jr and Daniel L Rubinfeld. "Hedonic housing prices and the demand for clean air". In: (1978).

[36] Noelwah R Netusil et al. "Valuing green infrastructure in Portland, Oregon". In: *Landscape and Urban Planning* 124 (2014), pp. 14–21.

most from it. This relationship presents a fantastic way to increase specific green infrastructure in the city without needing the same sized budgets as methods that focus primarily on mechanical infrastructure.

4 Incorporating future trends into urban planning

5.1 Biodiversity optimization.

The issue of maximizing biodiversity with these types of models is especially challenging, given that future trends will define early actions. Unfortunately, modeling the future impacts of climate change on ecosystems and habitat development is difficult at best.[37] Extreme variability in outcomes is observed with slight changes in parameters. In addition, critical habitats will be affected by urban planning decisions, infrastructure development, and any other process. Combining all of these effects into a decision on which land to conserve now for biodiversity optimization is explored thoroughly Groves et. all 2011[38], Estrella 2016[39], and Moilanen 2009[40]. There are two types of optimization problems for biodiversity management: the species-set covering problem and the maximal covering species problem. The former focuses on minimizing land parcels while covering all species for biodiversity. Using this type of optimization technique can also be applied to site features that support

[37] Craig R Groves et al. "Incorporating climate change into systematic conservation planning". In: *Biodiversity and Conservation* 21.7 (2012), pp. 1651–1671.

[38] Groves et al., "Incorporating climate change into systematic conservation planning".

[39] René Estrella, Dirk Cattrysse, and Jos Van Orshoven. "An Integer Programming Model to Determine Land Use Trajectories for Optimizing Regionally Integrated Ecosystem Services Delivery". In: *Forests* 7.2 (2016), p. 33.

[40] Atte Moilanen, Hugh P Possingham, and Stephen Polasky. "A mathematical classification of conservation prioritization problems". In: *Spatial conservation prioritization*. Oxford University Press, 2009, pp. 28–42.

species or large habitats. The latter focuses on maximizing the number of species covered with specific land parcels.

Early models for maximizing future biodiversity show scattered land plots as the optimal solution. Using this type of model brings up a host of issues surrounding migration, population scarcity, connectivity, predator-prey model imbalance, and others. By choosing to pick land parcels that are more dense in their plots, we solve or limit some of these issues. It's been suggested that this would actually better maximize future biodiversity.[41]

5.2 Land use trajectories and regional connectivity

By defining the set of land parcels needed for future biodiversity in the face of climate change, we can better plan for sustainable and lasting infrastructure for future urban spans. This helps planning for future energy needs and helps define urban impact on the surrounding ecosystems. There are two ways to think about this sort of optimization. We can plan urban development based on future expectations of ecosystems or focus on urban development and combat future climate change using built capital to supplement natural capital. It's easy to see that the latter represents n older way of thinking, without any sort of ecological optimization. By controlling future urban land use, based on the changing natural world, we can better preserve regional connectivity for a larger portion of species.

[41]Haight and Snyder, "Integer programming methods for reserve selection and design".

5 Conclusion

A wide range of integer programming applications is known and expanding, especially in optimization methods. While solely relying on this type of model is discouraged, using it to help guide research and current actions is encouraged. The chief concern for climate change modeling is that the outcomes are vastly different given small changes in initial variables. Although estimates are a good start, they are not exact and do not take into account every aspect. For this would be impossible given that models of this size are, at this stage, not developed.

Urban design in particular can benefit from land use trajectories, optimal habitat locations, and future regional connecting corridors. In this way we can build lasting infrastructure to achieve energy and environmental goals. Furthermore, a positive feedback loop exists whereby knowing more about future ecosystems can help us currently define better urban area development. Knowing this, we can be more sure of the impact these urban areas will have on the surrounding ecosystems that encompass them. This reduces uncertainty and helps create better reliability in the model. Finally, the need to plan for climate change is apparent, and the methods presented here seek to do just that.

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