

地理设计中的优化

Optimization in Geodesign

摘要 ·····

在景观决策中采用优化算法已经被看作是设计过程的对照。实际上，迈克尔·F·古特柴尔德已明确地将最优化、小尺度（small-d）设计归为运筹学和管理科学的一部分，并将其与隶属于景观设计与规划的大尺度（big-d）设计进行了区分^[1]。本文论证了通过优化技术与地理设计技术的结合，以促进形成而非缩小景观设计或规划的决策空间。古特柴尔德认为优化并不一定局限于形成单一的决策方案，而是通过对目标和限制因素（空间和全球性）的调控，产生一系列不同的决策方案。优化算法的优势在于众多的决策方案是位于非支配集中的。当用户使用交互式地理设计工具来勾勒形状和编辑属性时，无论以何种标准衡量，所得到的许多解决方案都将次于另一些解决方案。优化方法能够剔除这些劣等方案，有利于设计师和利益相关者的决策过程。空间及其属性抉择的互动过程非常重要；然而真正的挑战在于构建能够将这些功能与稳健优化算法相联系的系统。本文总结了森林管理和区域景观规划的各种可能性，并探索了抉择过程中的快速响应时间，这能够支持在非劣等方案间做出选择，以及应对随时间变化的不确定性和环境条件。

关键词 ·····

地理设计；优化；森林管理；区域规划

Abstract ...

The use of optimization algorithms in landscape decision-making has been seen as the antithesis of a design process. Indeed, Michael F. Goodchild clearly distinguished optimization, small-d design as part of operations research and management science, from big-d Design, which is the province of landscape architecture and planning^[1]. This paper argues a case for integration of optimization techniques and geodesign technologies to help shape, but not narrow, the decision space associated with a landscape design or planning situation. Optimization need not, as Goodchild argues, be limited to production of a single point in the solution space. By creative manipulation of objectives and constraints (both spatial and global) a disparate set of possible futures can be generated. The advantage of using optimization is that all these points within the solution space are on a non-dominated surface. When the user is limited to a set of interactive geodesign tools, sketching shapes and editing attributes, many of the generated solutions may be inferior, on all criteria, to another solution. Optimization removes these inferior solutions and makes it easier for the designer, and the stakeholders, to review the options and make decisions. The interactive processes of spatial selection and attribution are still important; the challenge is to build systems that link these capabilities to robust optimization algorithms. The paper reviews these possibilities in the context of forest management and regional landscape planning and explores options for achieving fast response times, which supporting selection among the non-inferior solutions and dealing with uncertainty and conditions that change over time.

Key words ...

Geodesign; Optimization; Forest Management; Regional Planning

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1 引言

1.1 地理设计的性质

迈克尔·F·古特柴尔德^[1]在寻求地理设计参数过程中，明确地将优化、小尺度设计归为运筹学和管理科学的一部分，并将其与隶属于景观设计和规划的大尺度设计进行了区分。多年来，学者们一直在探索优化算法（线性规划、目标规划和遗传算法）在土地利用优化布局中的应用，这是基于一系

列限制条件下最大化一个或多个目标的优化布局方式，而非单一地追求经济目标。^{[2][3]}与此同时，用于土地利用决策分析的GIS工具逐渐兴起^[4]。GIS是基于伊恩·麦克哈格^[5]、卡尔·斯坦尼兹等^[6]及他人提出的地图叠加理念而发展起来，这一理念早在GIS出现之前就已经形成。同时，景观设计师一直在利用类似方法（包括草图方式在内）进行工作。但多年以来，景观设计专业的学生一直不清楚自己为何

1 Introduction

1.1 The Nature of Geodesign

Michael F. Goodchild^[1], in seeking to set the parameters of geodesign, clearly distinguished optimization, small-d design and part of operations research and management science, from big-d Design, which is the province of landscape architecture and planning. Over many years, researchers have looked into the potential of optimization techniques (linear programming, goal programming, genetic algorithms) for creating land use distributions that maximize one or more, not purely economic, objectives within a set of constraints.^{[2][3]} Parallel to this activity has been the emergence of GIS tools for analysis of land use options^[4]. The latter has built upon map overlay concepts developed before the emergence of GIS by Ian McHarg^[5], Carl Steintiz, et al^[6] and others. Meanwhile landscape designers continued working primarily with analogue methods, including sketching, and for many years landscape architecture students wondered why they needed to study GIS.

Recently, driven in part by the GIS vendor Esri, there has been a movement towards incorporation of the sketching approach to landscape design (which can be taken to include broader scale planning) with the more rigorous analytics available through GIS. This combination has been given the name geodesign. Steintiz^[7] contends that geodesign is not itself new, but that rather it has new technologies at its disposal that change the character, but not the essence, of the process. His definition reads: geodesign is a design and planning method which tightly couples the creation of design proposals with impact simulations informed by geographic contexts, systems thinking, and digital technology^[7].

The final words suggest that you cannot do geodesign without technology and systems. This is also implied by “tightly couples” — a technology driven expression. That is, a user (or multiple users) has a platform for design, which also provides feedback on impacts. These are not two separate entities. All these components open the door for optimization. Steintiz also writes: “A principle advantage of the optimized way of designing is that it does not waste time”^[7]. This is also my principle argument.

1.2 Optimization in the Design Process

The design process can take many forms. If it involves use of spatial data (even if not always tightly coupled) it may be called geodesign. Whatever the name, it involves a series of stages beginning with the need for decisions and ending with decisions.

In any issue of moderate complexity, with decisions that have multiple levels of implementation, and many different spatial expressions of that implementation. There are effectively an infinite number of possible ways to alter the geography of the study area. Add to that the probability that there will be changes which will influence the future of the region, but are outside of the region's control (climate change is but one example), and that each of the many possible actions can occur in a range of possible contexts (scenarios). Some changes to an area can be quickly dismissed as inappropriate by anyone with interests and objectives within a “normal” range. Others may require some expertise to dismiss. A good designer, or design team, may be able to generate predominantly “good” options, but there are still potentially a great many of these. Then, for each option there is the need to determine what differences it will make, what methods need to be applied for realization, and elicitation of stakeholder feedback in relation to each option. This needs to be done under each of the plausible scenarios (not only climate change, but also perhaps demand for food and water, fire, the push towards renewable energy, the transition to GM-based agriculture, power-shifts in the world economy and changing sources and destinations of tourism).

With so many possibilities to consider the design team needs some assistance sorting the possibilities. However, as there is never a single objective — with a range of economic, environmental and social goals competing for favoritism — a clear rank ordering of the options is never possible. For different people, different options will be preferred, some might be not preferred but acceptable, while some may be unacceptable to one group of stakeholders. If ranking is not possible, can we still eliminate some options and hence save time?

The answer lies in identification of the Pareto set of non-dominated, or non-inferior, options. Suppose we can articulate three objectives and can measure the degree of

要学习GIS。

最近,在Esri的倡议和推动下,出现了一种通过GIS将景观设计中(包含尺度更大的规划)的草图手段和更为严谨的分析手段相结合的趋势。这种结合被称为地理设计。斯坦尼兹^[7]认为地理设计本身并非新生事物,它的创新在于更善于利用新技术来解决问题,这改变了设计过程中的某些特性,而其本质不变。他对地理设计的定义如下:地理设计是一种设计和规划方法,这种方法将设计方案的创作与基于地理环境分析、系统思考和数字技术应用的影响分析模拟耦合在一起^[7]。

该定义的最后部分说明,如果没有相应的技术和系统,地理设计是无法实施的。这一点在“耦合”——这个技术性的表述中——也有所体现。也就是说,一个用户(或多个用户)拥有一个设计平台,这个平台同时也为设计影响提供反馈。它们不是两个分离的部分。所有这些元素都为优化创造了途径。斯坦尼兹还写道:“优化设计方法的优点就在于能够避免浪费时间”^[7]。这也是我的主要观点。

1.2 设计过程的优化

设计过程可以呈现多种形式。如果其中涉及空间数据(即使这些数据并非总是紧密相关)的利用,也可被称作地理设计。不论被如何命名,设计的一系列过程都是始于决策,终于决策。

对于任何具有一定复杂度的问题,决策的实施是多层次的,且具有不同的空间表达形式。我们能够运用很多有效而可行的方法来改变区域的地理形态,有些改变将会影响区域的未来,而有些变化超出区域本身的可控范围(例如气候变化),每一种可能的改变都是基于一系列不同的情景。在合理的区间内,由于个体的目标和利益问题,有些改变能很快被排除掉,而其它改变的排除则需要专业人士进行判别。一个优秀的设计师或设计团队或许能够很快做出“好”的选择,但是仍然存在很多潜在的优选。对于每种选择,我们还需要明确它们可能产生的差异,需要什么样的措施才能将其实现,以及引导利益相关者针对每种选择给出反馈。以上这些需要在合理的情景设定下才能完成(不仅考虑气候变化,还包括食物和水的需求、防火、可再生能源使用、转基因农业、世界经济格局转变,以及资源及旅游目的地地的变化等因素)。

由于存在很多可能性,设计团队需要借助一些手段对这些可能性进行筛选。然而,目标向来不是

单一的——各种经济、环境和社会目标都需要予以考虑——对选择进行明确的排序是不可能的。不同人群的选择自然不同,某些选择可能并非首选但却可以接受,而另一些可能对某一利益相关者来说是不可接受的。如果排序无法实现,那么我们可否通过剔除选项从而节约时间呢?

答案就在于帕累托非支配集(或非劣解集)的确定上。假设我们可以明确3个目标,并且可以衡量每种选择实现这些目标的程度。如果A选择在所有3个衡量标准的排序上都高于B选择,那么我们就可以认为A选择优于B选择。由于没有人考虑B选择,该选择就不会进入下一轮考量。总之,某些选择在所有评价标准上都劣于其他选择,这些选择就是可支配的。如果这些选择被排除,那么我们就只有非支配或非劣选择。这样的选择集合被称为帕累托集。

帕累托集的数量仍然会非常大,而且不同的帕累托集都是基于每个未来外部条件而存在的。因此,决策难度虽然已经降低(劣解也已被剔除),但是进一步的问题还有待在下文中继续探讨。

2 优化框架的构建

就算法而言,广义上优化算法是基于单一目标的(例如,区域保护价值的最大化),该目标可以通过土地覆被类型(例如:可采伐森林、防护林、保育草场、牧场和农田)配置进行量化。目标由一组输入参数(例如土地覆被类型)及其空间分布所决定。因此,目标能够通过总和每种土地覆被类型所有面积的保护价值而得到量化。

当然,有一些诸如连接度这样的空间因素和关系会使量化过程变得复杂。这些可采用连接度指数进行量化^[8]或成为算法和设计之间一种模糊地带,设计师的专业知识将在其中发挥关键的作用(参见第3部分)。

最大化保护价值是相对直接的方法,它简单地将所有土地赋予了最优保护的覆被类型。然而,即使最优保护性土地覆被类型的确定非常简单,我们仍将给出一定的约束条件来确保解决方案的可行性。例如,各利益相关者一致认为该地区需要创造大量就业岗位或出产一定数量的木材。如果仅从最大化保护的角度出发对所有土地进行配置,那么,这些目标将无法实现。因此这些因素就会成为约束条件,并且也需要得到量化。如果我们增加最终的约束条件,即配置最优保护的面积不能超过该区的可用土地面积,那么可用土地覆被类

success that each option has in meeting these objectives. Then we can say that option A dominates option B if A is ranked above B on all three measures of achievement of objectives. Option B can then be eliminated from further consideration because no one will prefer option B. In general, any option that is inferior to some other option on all criteria is dominated. If these are eliminated then we have only non-dominated, or non-inferior, options. This collection of options is known as the Pareto set.

The Pareto set can still be very large, and a different Pareto set will exist for each set of future external conditions. So, while the difficulties of decision-making have been reduced — and the possibility of an inferior solution eliminated — there is still work to be done as explored in the following sections.

2 Framing the Optimization

Broadly, in computation, an optimization is framed as a single objective (for example, maximize the conservation value of the region) that should be quantifiable in some way based on allocation of land cover types (for example, harvestable forest, protected forest, protected pasture, grazing land, cropping). The objective is dependent on a set of input parameters (such as land cover types) and their spatial distribution. The objective can then be quantified as the sum of the conservation value of each area of each land cover type.

Of course there are spatial factors and relationships, such as connectivity, which complicate the quantification process. These could also be quantified using connectivity metrics^[8] or could be part of the blurred area between computation and design within which designer expertise has a key role to play (see Section 3).

Maximizing conservation value is relatively straightforward; simply give over all the land to the best land cover type for conservation. However, even if defining best land cover type for conservation were simple, there are going to be constraints that make this solution unviable. For example, it may be that there is consensus among stakeholders that the region needs to support a certain number of jobs or produce a certain amount of timber. These outcomes may not be achieved if all land is allocated so as to maximize conservation.

So, these other factors become constraints, which also need to be quantified. If we add the final constraint that the area of land allocated can be no more than the total area of available land in the region, then the available land cover types can be distributed such as to maximize the objectives while also meeting the constraints. This gives one point in the Pareto set.

If we then change the objective to, say, maximizing jobs and make conservation value a constraint, we generate another point of the Pareto set. Having generated all possible member of the Pareto set, we then need a mechanism to present these non-inferior solutions to stakeholders and to elicit a choice between them (see below).

However, if the climate changes significantly so will the distribution of jobs possible from grazing or cropping, and so may the relative conservation value of protected forest and protected pasture. For each set of plausible future conditions there is new set of coefficients, which would generate a new Pareto set.

3 Merging with Design

The question of how designer skills and sketch-type methods can be merged with optimization processes is considered in the context of a specific example in forest management. The project involved development of a number of spatially distributed management options where the different “land cover” types were different forest management regimes ranging in intensity from no timber harvesting, to clearfell-burn-and-sow (CBS) on a 65-year cycle. A GIS-based approach was developed^[9] which allowed users (with the assistance of a systems operator) to distribute forest management options and to see the consequences in term of 3 main indices (economic outcomes, environmental outcomes and amenity outcomes), which were divided into 8 sub-indices. The process for development of options is shown in Figure 1, and an example result in Figure 2. In Figure 1, the box on the left is from Smith et al^[9]; the “new capacities” on the right indicate the roles of the designer and the optimization process. Geodesign and optimization could be applied to steps 3, 4 and 5 in the selection of land for particular management systems. In this case, the objective would automatically be met.

型的分布就能在实现最大化目标的同时满足约束条件。这就在帕累托集中增加了一个点。

接下来, 如果我们将目标改为工作机会最大化, 而使保护价值成为一个约束条件, 那么我们就在帕累托集中产生另一个点。帕累托集中所有的可能点都产生后, 我们就需要一个能够向各利益相关者表达这些非劣解的机制, 并请他们做出一个选择(参见下文)。

然而, 如果气候变化非常显著, 就业分布将可能从放牧转向耕作, 有关保育森林和保育草场的保护价值也可能产生变化。对每个可能的未来条件集来说, 都将存在一个新的系数集, 并由此产生一个新的帕累托集。

3 与设计融合

设计师的技能与草图类的方法如何融入到优化过程中? 我们将结合一个具体的森林管理项目来探讨这个问题。该项目中涉及到多种空间分布管理的选择, 在这些选择中, 不同的“土地覆被”类型对应不同的森林管理制度, 其强度包括从无砍伐到以65年为周期的清伐-焚烧-播种制度。一种基于GIS的方法得到了应用^[9], 该方法使得用户能够(在系统操作员的协助下)对森林管理选择进行分配, 并通过经济产出、环境效益和舒适度3个指标(这3个指标下分为8个子指标)查看其效果。这个选择过程见图1, 相应的示例结果见图2。图1左侧的方框来自艾里克·L·史密斯等^[9]; 右侧的“新能力”表明了设计师的作用和优化过程。地理设计和优化算法能够在步骤3、4、5中被应用于特定管理体系中土地的选择中。在本案例中, 目标将会自动计算生成。

当地利益相关者选择了约25个不同的选项, 当然, 这个数字可能随参与者的增多而增加。一个人工且主观的过程将过滤掉那些受支配的选项, 剩余选项进入到评估阶段^[10]。对那些被剔除的选项来说, 生成该选项的2~3小时基本上被浪费了。但通过使用优化过程, 就会得到能够满足所有8个子指标的最优方案。

这一概念看似非常简单, 但实施时却相当复杂。在我们的研究区域内, 大约有18 000个多边形, 每个多边形都被赋予增长率、休闲价值、溪流临近度和其他因素的属性值。虽然这意味着大量的计算过程, 但仍存在简化的选择, 我们将在下面的章节予以讨论。此外, 一些因素难以量化, 例如视觉质量。这可能不仅取决于多边形本身, 还取决于

多边形视域内的其它多边形。对很多人来说, 优化可能看起来像一个“黑箱”^①, 并因此对其产生怀疑。因此, 我们需要让用户仍然对最终结果拥有绝对控制的感觉。

接下来, 我们将讨论上文提到的保护价值(如生物廊道)和视觉质量(整个视域效果)的空间关系问题。这部分将涉及到设计技能, 特别是基于这些复杂关系提出建议的能力, 这使能力能使优化可行, 并能够使利益相关者信服。有两种非常简单的方法可以让用户参与设计过程并拥有控制过程的感觉。

首先, 对特定区域进行预先的土地管理设计。为此, 设计师应当给出非常有力的经验佐证, 证明其在所有条件下都是合理的选择, 或给出一个社会共识, 说明其他选择都是无法被采纳的(如保护现有的国家公园)。这些区域随后将会从优化过程中被剔除, 并基于指定区域的生产力, 对约束条件进行调整。

其次, 设计师可通过调整系数对特定区域进行干预。如果他认为在现有人造林附近规划一个新林场有利于创造景观连续性, 那么为实现这个目标, 他就需要将一些多边形的木材生产系数略微调高(但仍在产量估计的不确定值域范围内)。鉴于利益相关者脑海中没有精确的边界概念, 这就需要以快速草绘的方式完成, 然后对草绘区域进行粗略界定(如增加该区域中的人造林)。随后, 对其余用地进行配置, 例如, 基于利益相关者选择的一系列约束条件, 实现木材产量最大化。

4 算法管理

减少计算量将有利于互动过程。在森林管理中, 我们无需保留所有的18 000个多边形和42个属性, 研究区域能够被划分成更少的土地等级。由于多边形是17个初级(如土地使用权、植被类型、径流等级)或次级(如缓冲区、建立时间和景观敏感度)数据层的集合, 这些多边形不可能在42个属性上完全一致。因此, 根据特殊属性进行聚类还是会生成相当大的决策空间^②。虽然优化过程中可以进行计算, 但很难快速反馈及支持互动性设计过程。另一种途径是同一土地等级的多边形间允许统计意义的相似度, 并非属性的相似。鲍勃·邦斯和他的同事们最初在坎布里亚(英国)对统计性土地分类进行了大量的探索^[11], 然后将这种探索扩展到整个英国^[12]和一些欧盟国家^[13]。毕夏普^[14]将

① “黑箱”是指那些只能得到其输入值、输出值和转换特性, 而不知道其内部结构的设备、系统或物体。

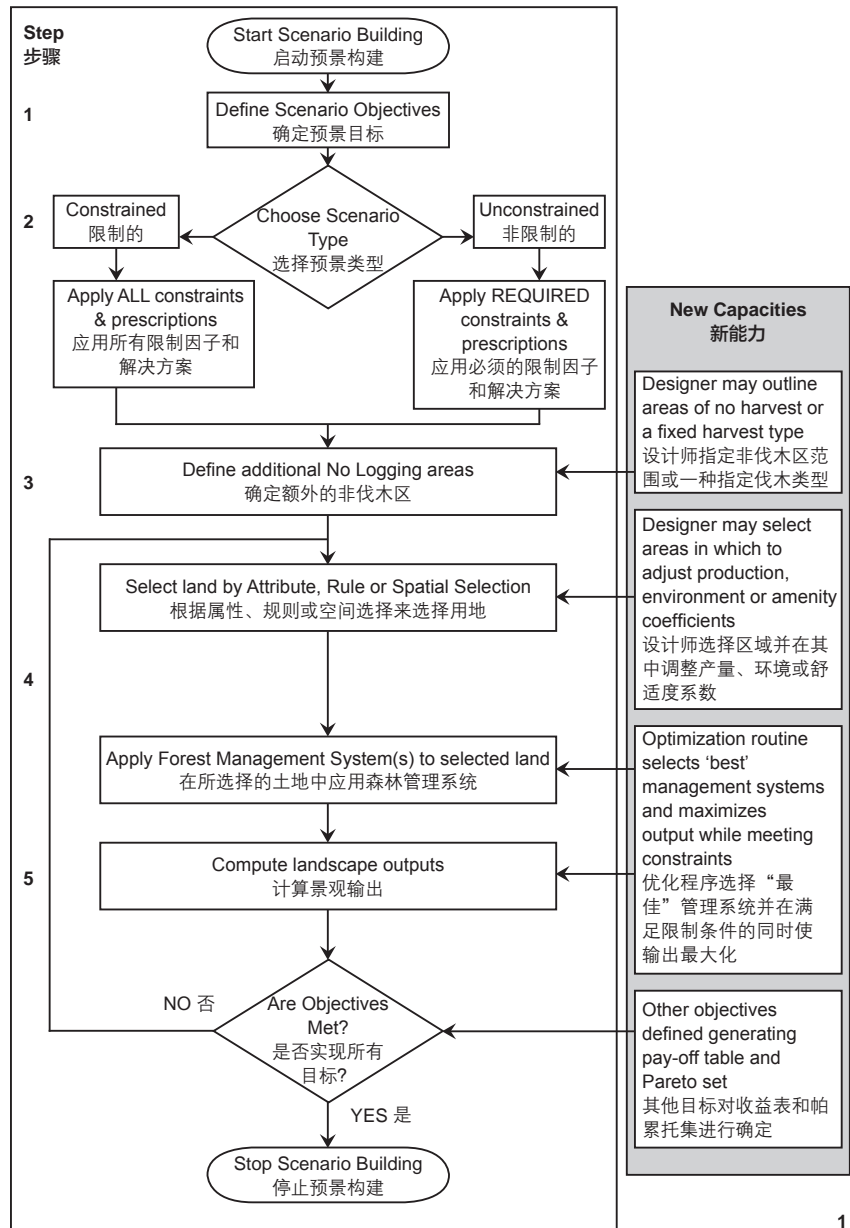
② 决策空间指在决策问题中有可能采取的决策方案的集合。

Around 25 different options were created by local stakeholders, but it could have more with more participants. A manual and subjective process was then applied to filter out those that were dominated, leaving the remainder to go into an evaluation phase^[10]. For those whose options were dropped, the 2 ~ 3 hours spent in creating them were essentially wasted. Had an optimization process been included a 'best' solution for each of the 8 sub-indicators could have been generated.

While the concept is simple, the implementation is potentially more complex. In our study area there were around 18,000 polygons, each with its own characteristics in terms of growth rates, recreational values, stream proximity and other factors. While this represents a great deal of processing for any algorithm, simplification options exist as discussed in the next Section. In addition, some factors can be hard to quantify, visual quality, for example, may depend not only on what happens in the polygon under consideration but on all the other polygons in the viewshed of the decision polygon. Optimization can also look like a “black box”^① solution to many people, which can lead to mistrust. Care must therefore be taken to give users the feeling that they still have significant control over the outcomes.

Then there is the issue of spatial relations already mentioned in the context of conservation value (for example, wildlife corridors) and visual quality (effects across a viewshed). This is an area in which some blending of design skills, particularly the ability to make proposals based on these complex relations, with optimization seems possible, and reassuring for the stakeholder. There are two quite simple ways in which the user can begin the process through design and have a sense of control.

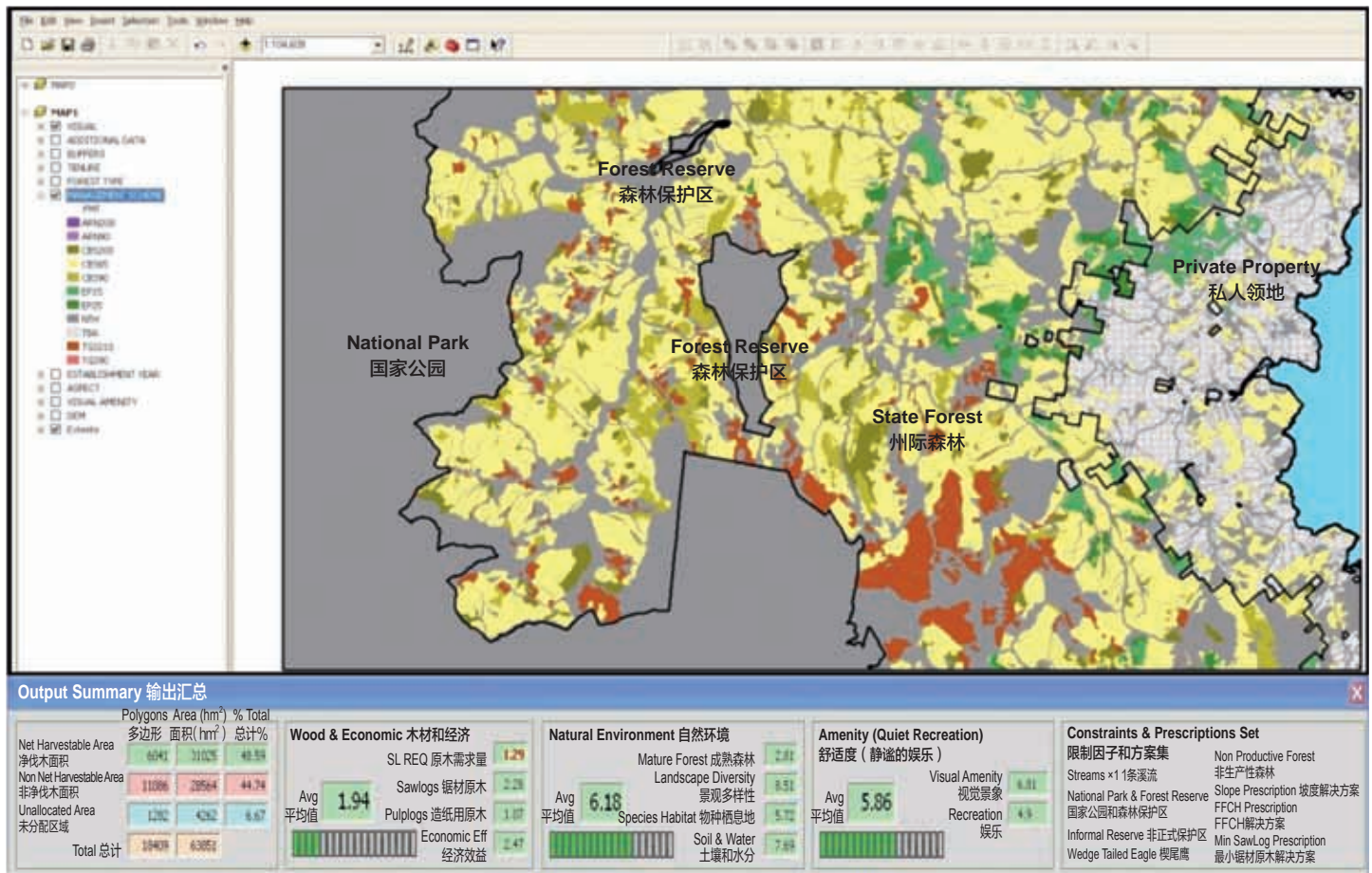
First, the land management may be designed in advance for certain areas. For this the designer should have strong empirical evidence that this was the appropriate option under all circumstances, or a community consensus that no other option would be tolerated (for example, protection of existing national parks). These areas would then be removed from the optimization process and the constraints adjusted based on the productivity of the designated areas.



Secondly, a designer could intervene by adjusting coefficients within certain area. A designer thinks it would be good for landscape continuity to put new areas of plantation forestry near to existing plantations. To achieve this some polygons could have their timber production coefficient under plantation increased slightly (within the uncertainty limits of the production estimates). Given that the stakeholder does not have precise boundaries in mind, this could be done as a quick sketch operation, followed by a loosely defined

① Black Box is a device, system or object which can be viewed in terms of its input, output and transfer characteristics without any knowledge of its internal workings.

1. 森林管理选择开发的5个过程
1. Five-step process for development of forest management options



邦斯等人^[1]的分类作为线性规划法的基础，应用到英国坎布里亚农村土地利用决策中。在毕夏普的模型中，输出变量是木材产量、食品和能源产量（其中肉和奶都是单独项）、就业人数、能源输入要求、休闲潜力和保护价值。这些输出项通过包括软木、硬木、作物、羊肉、牛肉、奶制品和“野生资源”在内的土地利用产出。总共有90个决策变量。以每个输出变量为目标，以其他输出变量为约束条件，模型运行9次，得到一份收益表（表1）。该表显示了帕累托集可能成效的范围。

在本案例中，此分类过程将6 200个1km²的栅格减少为16种土地类别（其中15个用于分析）。在一台使用了4年的笔记本上运行一个名为“求解程序”的Excel扩展程序，仅需50秒就完成了优化计算。如果计算时间随决策变量呈线性增长（最理想的情况），那么6 000个多边形（6种土地利用）问题所需的时间是1个具有15个土地类型的多边形的400倍，也就是说，用同样的设备需要7小时才能完成。

在没有大型硬件支持的情况下，地理设计显然是不可行的。一些降低问题复杂性的机制就变得至关重要，如土地利用分类。

优化过程的下一步是运用草图机理划分特殊区域，这将简化优化过程。一个适宜的用户界面应当能够划分出草绘区域，并且对所有或部分交错土地分类的条件进行调整。例如在坎布里亚案例中，一个粗略确定的具有额外就业价值的区域可能仅适于那些包含居住基础设施的土地类型。

5 非劣解的选择

除非利益相关者或利益相关组织有明确的单一目标界定，否则就会产生多个非劣解。这样问题就变成了在解决方案中进行选择。选择的方式既可以是数学性的，也可以是非数学性的。非数学性选择方式有很多种，可以通过投票或工作会议来寻求共识。然而，多个输出因素导致决策空间仍非常复杂，人们可能需要专业协助才能够理解这些选择产

2. 管理分布案例和指标值显示面板（图片来源：参考文献[9]）
2. A sample management distribution and the panel showing indicator values (Source: Refs.[9])

action applying to the sketched area (for example, increase preference for plantation in this area). The remaining allocations would then follow as, for example, timber production was maximized against the range of constraints selected by the stakeholder.

4 Managing the Computation

Easing the computational burden gives the potential for an iterative process. Instead of retaining all 18,000 polygons and 42 attributes, in the forest management case, the area of interest could be classified into a smaller number of land classes. Given that the polygons were defined on the basis of intersection of 17 primary (for example, tenure, vegetation type, stream class) or secondary (for example, buffers, establishment year, visual sensitivity) data layers, it is unlikely that a larger number of polygons would be identical on all 42 attributes. So, clustering by unique identity would still leave a very large decision space^②. While this would be computable in an optimization procedure, it would be very unlikely to give rapid feedback and support an interactive design process. The alternative is to allow some degree of statistical similarity, rather than identity, between polygons within a land class. Statistical land classification has been widely explored by Bob Bunce and colleagues initially in Cumbria (UK)^[11], then for the whole UK^[12] and also for the EU countries^[13]. Bishop^[14] used the Bunce and Smith^[11] classification as the basis

for a linear programming approach to rural land use decision-making in Cumbria, UK. In Bishop’s model the output variables were timber production, food energy production (including meat and milk as separate items), employment, energy inputs required, recreational potential and conservation value. The outputs were generated by land uses including softwoods, hardwoods, cropping, sheep, beef, dairy and “wilderness”. There were 90 decision variables in all. Running the optimization nine times with each output as the objective, and the other outputs as constraints produces a pay-off table (Table 1). This shows the range of possible achievements within the Pareto set.

The classification process, in this case, reduced approximately 6,200 1 km-square grid cells down to 16 land classes (of which 15 were used in the analysis) and the optimization takes about 50 seconds on a 4-year-old laptop using “Solver”, an Excel extension (www.solver.com). If the compute time increases linearly (the best case) with the number of decision variables, a 6,000 polygon (and 6 land use) problem would take over 400 times the length of one with 15 land classes, i.e. over 7 hours on the same equipment. This is clearly unworkable in a Geodesign context without special hardware. Some mechanism to reduce problem complexity, such as the use of land classes is essential.

Once that is done, the sketch-based mechanism for separating special zones could be included in a

② Decision space is an assemblage of all possible solutions to a certain decision.

表1 坎布里亚收益表
Table 1 Pay-off table for Cumbria

Output 输出 Objective 目标	Timb 木材	Meat 肉类	Food Ener. 食物能源	Recr. Pot. 休闲潜力	Ener. Input 能源输入	Cons. Val. 保护价值	Labor Input 劳动力输入	Milk 牛奶	Wool 羊毛
Timber 木材	+134				+6	+2	+9	+13	
Meat 肉类		+8			+7	+5	+7	+11	
Food Energy 食物能源			+49		+13	+5	+25	+58	
Recreation Potential 休闲潜力				+11	+1	+8	+4	+13	
Energy Input 能源输入					-3	+3			
Conservation Value 保护价值				+5	+2	+12	+4	+13	
Labor Input 劳动力输入			+45		+13	+5	+24	+54	
Milk 牛奶		+3	+34		+13	+5	+19	+64	
Wool 羊毛					+2	+5	+5	+12	+56

*在这些解决方案中，能源输入水平不受限制，但其他因素的输出均设定为其根据现状作出的估计值。数据为相对于现状水平的百分比变化。
*In these solutions, energy input levels were not constrained but outputs of other factors were set to their estimated current levels. The numbers are the percentage change relative to current levels.

生的影响。可视化可以作为一种非常重要的辅助手段，帮助人们就备选方案进行有效的沟通。如果视觉表达是自动生成的，并且在设计和决策过程中就能够实现，那么这种方法就会变得更加有效。在景观领域中，可视化与GIS的耦合已成为许多景观研究的课题。一款名为CommunityViz的软件率先在GIS要素和系统模型与可视化软件包之间实现了实时联系，尤其适用于社区决策中^[15]。随着GIS对3D表现（如Esri CityEngine）支持程度的日益加大，现在有许多方法可以实现对优化支持下的地理设计进行实时表达。

最简单的数学选择方法是针对个体目标使用线性权重目标方程，这将生成单一解。然而，许多问题仍有待商榷。尤其是人的权重不可能在所有等级的输出中都保持一致。通常，商品的重要性随着拥有量的增长会出现下降。如果我们假设效用变化本身为线性，而非阶梯形，那么每个解的总效用就是一个二次方程——在简化的坎布里亚案例中，这样还是会有4 000个变量——最佳解的寻找就要应用二次规划算法。

在通过连续优化得到的效益表（表1）中隐含了一些效益流失。米兰·泽莱尼认为这些效益水平的变化可以作为目标权重的基础^[16]。彼得·尼茨坎普和皮特尔·里特维德^[17]也寻求使用效益表作为循环计算的基础来获得偏好解。他们使用效益表来通过下式确定一个唯一的权重集：

$$\lambda = P^{-1}i (i^T P^{-1}i)^{-1}$$

式中P是效益矩阵，i是单位列向量。接着，使用这些权重的组合目标函数被最大化，利益相关者根据结果调整其约束条件集，就可以得到一个新的效益表，重复该过程直到获得理想解。

6 时间问题和不确定性

优化方法的实施仍存在许多挑战，但更大的挑战在于功能性的问题。后者包括时间因素，比如技术改变、可持续性和因子系数的不确定性。时间因素包括农业生产力的显著变化，例如转基因能够减少化学药品使用量从而提高产量、降低能源输入或提高保护价值。如果坎布里亚研究在2013年就得实施，那么固碳极有可能变成一个新的目标或约束条件，并成为效益表中重要的一部分。

因为敏感性分析可以判别结果是否对假设（即系数）敏感，以及其敏感程度，所以优化过程在这一背景下能够发挥很大的作用。单纯型算法得到的

对偶变量表明了结果和约束因素（即要求）的关系。这些算法的应用都是非空间的，但我们可使其变成空间化的，将不同的结果假设应用于特定土地类型，甚至是地图中的特定草图区域中。

7 结论

本文结合实证案例探讨了优化算法如何通过剔除所有劣解并提供在非劣解中进行选择的方法，来支持地理设计过程。设计师的专业知识和技能能够通过对这些具体、明确或粗略定义的区域进行划定得以体现，例如某些区域特别适宜某种用途或者某些区域不适宜某种用途（可通过输出系数的调整来实现）。设计师可获得的细致程度取决于在保证可接受的响应时间的前提下，对适宜用户界面的开发、土地分类方法的界定和适宜的空间分辨率。在不到1分钟的时间内即可获得最优解，这对于互动性、迭代设计工作来说是有意义的，超过这个时间就会让人感到失望。

采取这种方法也许并不像起初看起来那样，是一个很大的进步。根据上文的定义，地理设计包括“通过地理背景生成影响模拟”，这与设计过程紧密相连。影响模拟的生成需要一个与优化要求非常相似的输入数据范围和输出系数。GIS通常被认为是地理设计的基础（这也确实是迈克尔·巴蒂定义的一部分^[18]），为影响模拟或优化提供了必要的启动条件。

我认为优化和地理设计不应被看作景观管理或土地利用选择中两个分离的方法。这项技术使传统手段和设计紧密联系，从而对多维输出项或影响进行系统评估；同时，假设计算问题是可控的，而且过程可重复，那么，最终也能实现最优化。最优化并不会控制我们，我们仍然拥有决定权和主导权。LAF

process without adding greatly to the complexity of the optimization. A suitable user interface would also include the capacity to specify that the sketched area would alter conditions in all the intersected land classes, or just some of them. In the Cumbria case, for example, a loosely defined area of additional employment value might only apply to those land classes that include settlement infrastructure.

5 Selection among Non-Inferior Solutions

Unless the stakeholder, or community of stakeholders, has a very clear definition of a unitary objective, there are going to be multiple non-inferior solutions. It then becomes a problem of choosing among the solutions. This may be approached mathematically or non-mathematically. There are many ways to approach the choice without maths, a vote could be conducted or the options could be presented in a workshop and consensus sought. There remains, however, the problem that, with multiple output factors the decision space is still complex and people may need tailored assistance to understand the implications of the options. Visualization can be a significant aid to effective communication of alternatives, but will become more effective if the visual representations are generated automatically and are available during the process of design and decision-making. Direct linkage of visualization to GIS has been the subject of a number of studies in the landscape context. The software CommunityViz was perhaps the first to link the elements of GIS and systems modelling to a visualization package in real-time specifically for community decision-making^[15]. With GIS increasingly supporting 3D representation (for example, Esri CityEngine) there are many opportunities for real-time representation of optimization-supported approaches to geodesign.

The simplest mathematical approach to selection of a solution is to apply a linear weighted objective function over the individual objectives. This creates a unique solution. However there are many issues. In particular it is unlikely that people's weights would be the same at all levels of output. Typically the importance of a commodity declines the more one has of it. If the change in utility is itself assumed to be linear, rather than a

step, then the total utility for each solution is a quadratic function — in the simplified Cumbria case this would still have 4,000 variables — and an optimum solution can be found using a quadratic programming algorithm.

There are implicit trade-offs inherent in the pay-offs generated by successive optimizations (Table 1). Zeleny suggested that these variations in attainment level could be the basis for objective weighting^[16]. Nijkamp and Rietveld also sought to use a pay-off table as a basis for iteration towards a preferred solution^[17]. They used the pay-off table to define a unique set of weights given by:

$$\lambda = P^{-1}i (i^T P^{-1}i)^{-1}$$

where P is the pay-off matrix and i is a unit column vector. The combined objective function using these weights is then maximized and the stakeholder adjusts his/her constraint set in the light of the results. A new pay-off table is generated and the process repeated until an “ideal” solution is reached.

6 Temporal Issues and Uncertainty

While there remain challenges within the degree of optimization implementation described here, there are greater challenges moving on to further levels of functionality. The latter include dealing with temporal factors, such as technology change and long-term sustainability and also coming to terms with uncertainty in the factor coefficients. Temporal factors could include significant changes in the productivity of agriculture; for example genetic modifications which significantly increase yields, reduce energy inputs or enhance conservation values through reduced chemical usage. If the Cumbria study were implemented in 2013, carbon sequestration would very likely become a new objective / constraint and an important part of the pay-off table.

The optimization process can be helpful in this context because sensitivity analysis can tell us whether the outcomes are sensitive to the assumptions (for example, coefficients) and to what degree. Dual variables, as generated by the simplex algorithm, show the relationship between outcomes and constraints (for example, requirements). These are non-spatial in their typical applications, but could be made spatial by applying different outcome assumptions within

specific land classes or even within specific areas sketched onto a map.

7 Conclusion

The examples discussed here show how optimization may be able to support the process of geodesign by removing from consideration all inferior solutions and providing an approach to selection among the non-inferior solutions. The expert knowledge and skills of the designer can still be expressed through designation of particular, explicit or loosely defined areas deemed to be especially suitable for some purpose (as expressed through a change in output coefficients) or restricted to a particular use. The degree of subtlety available to the designer depends on further exploration of the appropriate user interface, the ways land classes are defined and the degree of spatial discrimination possible while retaining workable response times. Less than 1 minute to generate an optimum is probably workable in an interactive, iterative design context, any longer would be too frustrating.

Moving to this kind of approach may not be as large a step as it first seems. According to the definition above geodesign includes “impact simulations informed by geographic contexts” tightly coupled with the design process. Generation of impact simulations requires a very similar range of input data and output coefficients to those required for optimization. The GIS base commonly proposed as a basis for geodesign (and indeed part of its definition for Batty. ^[18]) provides the essential starting condition for either impact simulation or optimization.

I have argued that optimization and geodesign should not be regarded as two distinct approaches to allocation of landscape management or land use options. The technology which allows for tight coupling of traditional approaches to design, with systematic evaluation of multi-dimensional outputs or impacts, also lend itself to optimization, provided the size of the computation problem can be controlled such that the process can be iterative. The optimization does not need to control us; we can still have discretion and authority. **LAF**

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