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基于群决策的基础设施可持续性影响因素评价

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摘要：针对基础设施可持续性影响因素复杂，传统的可持续性评价方法难以客观评估基础设施可持续性影响因素的权重，构建了基于关联度的多属性群决策模型，引入综合权重修正矩阵，从信息偏差、一致性和信息熵三个方面对可持续性影响因素权重进行优化，并以实际项目数据为依据，通过实证分析验证了模型的有效性. 该评价模型的应用有助于提高基础设施可持续性评价的客观性.

关键词：基础设施；可持续性；影响因素；关联度；多属性群决策模型
中图分类号：N949　　**文献标志码**：A

Assessment of Influence Factors of Infrastructure Sustainability Based on Group Decision-making Model

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Abstract：According to the issue that the influence factors of infrastructure sustainability (IS) are abundant and complex，which generates that traditional evaluation methods are difficult to objectively analyze the weight of influence factors of IS. According to this issue，the multi-attributes group decision-making model is established based on the relation degree theory，and introduces comprehensive weight-modification matrices and optimizes the weight of influence factors of IS from three aspects：information deviation，consistency and information entropy. And the model is verified by the empirical analysis in terms of practical project data. The application of this model would improve the objectivity of the evaluation of IS.

Key words：infrastructure；sustainability；influence factors；relation degree；multi-attribute group decision-making model

基础设施在促进城市经济可持续发展、提高城市居民生活水平和减少贫富差距等方面都发挥着重要的作用[1-2]. 然而，我国在基础设施的建设和运营等阶段仍存在着长期利益的忽视[3]、生态环境的破坏[4]、使用寿命短[5]、运营管理水平低[6]等问题，其产生的根源在于对基础设施可持续性的忽视. 因此，在决策阶段对基础设施可持续性影响因素进行识别，有利于减少基础设施建设与运营过程中可持续性问题的产生.

影响基础设施可持续性的因素来自多层次多维度. 有些学者将基础设施可持续性分成三个维度进行评价和分析，即经济、社会和环境. 比如，Pryn[7]、Karaca[8]、Zhang[9]、Yao[10]等从经济、社会和环境三个维度评估和分析了基础设施可持续性；Shen 等[11]基于模糊集理论从经济、社会和环境三方面研究了基础设施可持续性的关键影响因素. 除此之外，部分学者也从其他方面考虑了基础设施可持续性影响因素. 比如，Zhou 等[12]将基础可持续性分为内部可持续性和外部可持续性，考虑了项目本身的经济技术和管理水平影响因素，进而建立了项目的可持续性评估模型. Boz 等[13-14]将基础设施可持续性分为产品工序和自然属性两方面，并通过专家访谈对其进行了验证分析. 然而，在以往的研究中，指标权重的确定主要依赖于少数专家的主观评价值，难以克服评价结果具有较强主观性的缺点. 徐选华等[15]提出了基于项目历史数据的关联度模型来评价复杂生态系统风险性. 虽然该模型克服了评价方法主观性强的缺点，但仅适用于单个对象的评价，且权重模型优化不足.

基于此，本文首先通过文献回顾对基础设施可持续性影响因素进行了识别，其次对单个项目可持续性影响因素的权重进行确定. 进而在考虑信息偏

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差、一致性和信息熵三方面因素的基础上，构建了基于关联度的基础设施可持续性多属性群决策模型. 最终通过对 24 个公路项目进行实证分析，验证了该模型的可行性.

1　基础设施可持续性影响因素识别

本文通过文献回顾[7-14]，参考国内的项目竣工环境保护验收报告，将基础设施可持续性影响因素分为经济因素（ECE）、社会因素（SOE）和自然环境因素（ENE），见表 1.

表 1　基础设施可持续性影响因素及量化指标

Tab.1　Sustainability factors and quantitative indexes of urban infrastructure

	影响因素	量化指标
经济因素（ECE）	投资资金合理性（IFS）	年成本占总投资比例（CTR）
		年收益占总投资比例（PTR）
		内部收益率（IRR）
	环保投资力度（EI）	环保投资占总投资的比例（EIR）
	投资回收周期（LCC）	投资回收周期（LCC）
	项目带来的经济效益（EB）	经济效益费用比（BCR）
	为经济发展提供便利设施（NEA）	辅助设施数量（NA）
		需求/供给（初期）（MSD）
社会因素（SOE）	对公众的影响程度（SI）	征地面积（LAS）
		拆迁面积（RS）
	公众满意度（SD）	公众满意度（SD）
自然环境因素（ENE）	自然生态影响（NE）	耕地占用（ALS）
		林地占用（WLS）
		生物多样性影响程度（BI）
		填挖平衡率（FER）
	水环境影响（WE）	pH 值
		悬浮物（SS）
		生物需氧量（BODs）
		重铬酸盐指数（CODcr）
		氨氮（NH_3-N）
		石油类（PC）
	大气环境影响（AE）	二氧化氮（NO_2）
		施工微尘（TSP）
	固体废弃物（SR）	弃土渣方
		废物（W）
	声环境影响（VE）	影响距离（IR）

2　基础设施可持续性影响因素权重优化模型的构建

2.1　相关概念的定义

将单个基础设施可持续性影响因素看成一个群体 $\boldsymbol{\Omega}$，其中包含表 1 中的 27 个可持续性影响因素量化指标. 具体定义如下：

定义 1　可持续性矢量. 设第 i 个可持续性影响因素的量化指标为 q 个，其中第 l 个量化指标对基础设施可持续性影响为 v_{il}（$v_{il}>0, l=1,2,\cdots,p$），则称可持续矢量 $\boldsymbol{V}_{il}=(v_{i1},v_{i2},\cdots,v_{ip})$ 为第 i 个可持续性影响因素的可持续矢量.

定义 2　可持续标准值矢量. 设第 i 个可持续性影响因素中第 l 个量化指标的可持续标准值为 $\bar{v}_{il}$（$\bar{v}_{il}>0,\ l=1,2,\cdots,p$），则称可持续标准值矢量 $\bar{\boldsymbol{V}}_{il}=(\bar{v}_{i1},\bar{v}_{i2},\cdots,\bar{v}_{ip})$ 为第 i 个可持续影响因素的可持续标准值矢量.

定义 3　两个可持续性影响因素 $\boldsymbol{V}_i$ 和 $\boldsymbol{V}_j$ 之间的可持续性关联度[15] $r_{ij}(\boldsymbol{V}_i,\boldsymbol{V}_j)$ 表示为

$$r_{ij}(\boldsymbol{V}_i,\boldsymbol{V}_j)=\frac{|\boldsymbol{v}_i-\bar{\boldsymbol{v}}_i|\cdot\boldsymbol{B}\cdot|\boldsymbol{v}_j-\bar{\boldsymbol{v}}_j|^{\mathrm{T}}}{\|\boldsymbol{v}_i-\bar{\boldsymbol{v}}_i\|_2\cdot\|\boldsymbol{B}\|_2\cdot\|\boldsymbol{v}_j-\bar{\boldsymbol{v}}_j\|_2}\tag{1}$$

其中 $\boldsymbol{B}$ 为第 i 个可持续性影响因素与第 j 个可持续性影响因素之间的量化指标影响关系矩阵. 矩阵 $\boldsymbol{B}$ 由可持续影响度 b_{lk}^{ij} 构成，b_{lk}^{ij} 表示第 i 个可持续性影响因素的第 l 个量化指标（$l=1,2,\cdots,p$）与第 j 个可持续性影响因素的第 k 个量化指标（$k=1,2,\cdots,q$）之间的影响度.

其中 $b_{lk}^{ij}=\dfrac{\min(p_{il},p_{jk})}{\max(p_{il},p_{jk})}$；$p_{il}=\dfrac{|v_{il}-\bar{v}_{il}|}{\bar{v}_{il}}$，$l=1,2,\cdots,p$；$p_{ik}=\dfrac{|v_{jk}-\bar{v}_{jk}|}{\bar{v}_{jk}}$，$k=1,2,\cdots,q$

定义 4　基础设施两个不同阶段的可持续性影响因素权重矢量 $\boldsymbol{w}_i$ 和 $\boldsymbol{w}_j$ 之间的相关程度用关联度[16] $\rho_{ij}(\boldsymbol{w}_i,\boldsymbol{w}_j)$ 表示为

$$\rho_{ij}(\boldsymbol{w}_i,\boldsymbol{w}_j)=\frac{|\boldsymbol{w}_i-\bar{\boldsymbol{w}}|\cdot|\boldsymbol{w}_j-\bar{\boldsymbol{w}}|^{\mathrm{T}}}{\|\boldsymbol{w}_i-\bar{\boldsymbol{w}}\|_2\cdot\|\boldsymbol{w}_j-\bar{\boldsymbol{w}}\|_2}\tag{2}$$

其中，$\boldsymbol{w}_i$ 和 $\boldsymbol{w}_j$ 分别是第 i 个阶段和第 j 个阶段可持续性影响因素的权重矢量. $\bar{\boldsymbol{w}}$ 是项目的平均权重矢量.

定义 5　在计算指标综合权重过程中，引入文献中成员矢量之间的关联度均方差和矢量集一致性指标作为评价标准. 相对偏差函数取得最小值时，表示每个项目权重矢量与群体综合权重偏差最小，一致性程度最高[17]. 据此构造成员矢量之间关联度的相对偏差函数：

$$f(\boldsymbol{W})_{\min}=\min\sqrt{\frac{1}{C_m^2}\sum_{1\leqslant i\leqslant j\leqslant m}(\rho_{ij}(\boldsymbol{w}_i,\boldsymbol{w}_j)-\rho(\boldsymbol{W}))^2}\Big/\rho(\boldsymbol{W})\tag{3}$$

其中 $\rho(\boldsymbol{W})=\dfrac{1}{C_m^2}\sum\limits_{1\leqslant i\leqslant j\leqslant m}\rho(\boldsymbol{w}_i,\boldsymbol{w}_j)$ 表示项目群体权重集 $\boldsymbol{W}$ 的一致性指标.

将准则权重 $\boldsymbol{w}_{tr}$ 理解为第 r 个可持续性影响因素

在准则集中所占比重,即“概率”. 用 Shannon 信息熵[18] $H_{(t)}=-\sum_{r=1}^{n} w_{tr}\ln w_{tr}$ 表示在项目第 t 阶段时可持续影响因素为项目可持续性提供的影响程度. 因此,项目 m 个阶段的总信息熵可以表示为

$$H_m(\boldsymbol{W})=-\sum_{t=1}^{m}\sum_{r=1}^{n} w_{tr}\ln w_{tr} \tag{4}$$

2.2 基于关联度的多属性群体决策模型的构建

基于关联度的多属性群体决策模型构建的流程如图1所示.

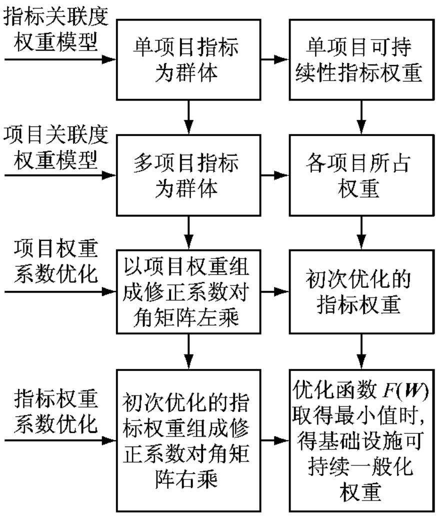

图1 模型构建流程图

Fig.1 Model build flow chart

利用关联度权重模型[15],对单个基础设施项目可持续性进行评价,得到单个项目基础设施可持续性评价指标权重. 然而,一个项目得到的可持续性影响因素权重对其他各类项目的借鉴程度有限,需要考虑多个基础设施项目的综合情况. 因此,在单个项目权重基础上,进一步将不同的项目看作一个群体 $\boldsymbol{\Psi}$,形成一个群体属性维度相同的多属性群决策问题. 关联度多属性群体决策模型的构建具体流程如下:

(1)运用关联度模型可得出 m 个项目可持续性影响因素权重,其中,第 t 个项目的权重矢量记为 $\boldsymbol{w}_t=(w_{t1},w_{t2},\cdots,w_{tn})$,$1\leqslant t\leqslant m$. 将 m 个项目可持续性影响因素的权重矢量矩阵记为:$\boldsymbol{W}=\{w_1,w_2,\cdots,w_t,\cdots,w_m\}$.

(2)运用式(2)分别计算出两个项目之间的可持续性相关度 $\rho_{ij}(\boldsymbol{w}_i,\boldsymbol{w}_j)$,形成 $m\times m$ 关联度矩阵. 根据标准化处理公式 $\boldsymbol{w}_t^*=\dfrac{\rho_{tt}(\boldsymbol{w}_t,\boldsymbol{w}_t)}{\sum_{h=1}^{m}\rho_{th}(\boldsymbol{w}_t,\boldsymbol{w}_h)}$,$t(h)=1,2,\cdots,m$,计算出每个项目在项目群体中所占的权重矢量,该权重的大小是由单个项目与其他所有项目的相关度决定,所占权重较大的项目则更接近项目群体综合权重. 记为:$\boldsymbol{W}^*=(\boldsymbol{w}_1^*,\boldsymbol{w}_2^*,\cdots,\boldsymbol{w}_t^*,\cdots,\boldsymbol{w}_m^*)$.

(3)项目权重组成对角矩阵形成修正系数矩阵,然后右乘初始的可持续影响因素权重矩阵 W,最终得到矩阵 $\boldsymbol{G}$:

$$\boldsymbol{G}=\begin{bmatrix} w_1^* & 0 & 0 & 0 & 0\\ 0 & w_2^* & \cdots & 0 & 0\\ \vdots & \vdots & \vdots & \vdots & \vdots\\ 0 & \cdots & 0 & w_{m-1}^* & 0\\ 0 & 0 & 0 & 0 & w_m^* \end{bmatrix}\cdot \begin{bmatrix} w_{11} & w_{12} & \cdots & w_{1,n-1} & w_{1n}\\ w_{21} & w_{22} & \cdots & w_{2,n-1} & w_{2n}\\ \vdots & \vdots & \vdots & \vdots & \vdots\\ w_{m-1,1} & w_{m-1,2} & \cdots & w_{m-1,n-1} & w_{m-1,n}\\ w_{m1} & w_{m2} & \cdots & w_{m,n-1} & w_{mn} \end{bmatrix} \tag{5}$$

对矩阵 $\boldsymbol{G}$ 每一列求均值,得到对应的项目可持续性影响因素权重值为 $\bar{w}_r=\dfrac{\sum_{t=1}^{t=m} w_t^* w_{tr}}{m}=\dfrac{\sum_{t=1}^{t=m} g_{tr}}{m}$,$r=1,2,\cdots,n$. 从而得到初次优化后可持续性影响因素的综合权重矢量为:$\bar{\boldsymbol{W}}=(\bar{w}_1,\bar{w}_2,\bar{w}_3,\cdots,\bar{w}_n)$

(4)为了让每个项目的指标权重更好地反映综合权重,将上一步优化后得到的可持续性影响因素权重值矢量 $\bar{\boldsymbol{W}}$ 组成对角矩阵,形成优化系数矩阵. 而后,将该优化系数矩阵右乘矩阵 $\boldsymbol{G}$,得到进一步优化的权重矩阵 $\boldsymbol{B}$:

$$\boldsymbol{B}=\begin{bmatrix} g_{11} & g_{12} & \cdots & g_{1,n-1} & g_{1n}\\ g_{21} & g_{22} & \cdots & g_{2,n-1} & g_{2n}\\ \vdots & \vdots & \ddots & \vdots & \vdots\\ g_{m-1,1} & g_{m-1,2} & \cdots & g_{m-1,n-1} & g_{m-1,n}\\ g_{m1} & g_{m2} & \cdots & g_{m,n-1} & g_{mn} \end{bmatrix}\cdot \begin{bmatrix} \bar{w}_1 & 0 & \cdots & \cdots & 0 & 0\\ 0 & \bar{w}_2 & 0 & \cdots & \cdots & 0\\ \vdots & 0 & \cdots & 0 & \cdots & 0\\ \vdots & \vdots & 0 & \ddots & 0 & 0\\ 0 & 0 & \vdots & 0 & \bar{w}_{n-1} & 0\\ 0 & 0 & \cdots & \cdots & 0 & \bar{w}_n \end{bmatrix} \tag{6}$$

对矩阵 $\boldsymbol{G}$ 每一列求均值,得到对应列指标的权重值为 $\bar{w}_r^*=\dfrac{\sum_{t=1}^{t=m} g_{tr}\bar{w}_r}{m}=\dfrac{\sum_{t=1}^{t=m} b_{tr}}{m}$,$r=1,2,3\cdots n$. 经

过再次优化得到可持续性影响因素综合权重为：$\bar{W}^{*}=(\bar{w}_1{}^{*},\bar{w}_2{}^{*},\cdots,\bar{w}_n{}^{*})$.

(5)根据群体偏差最小以及信息熵最大原则，本研究提出权重最优化模型(7)如下：

目标函数：

$$F(\boldsymbol{W})_{\min}=\min\sqrt{\frac{1}{C_m^2}\sum_{1\leqslant i\leqslant j\leqslant m}(\rho_{ij}(\boldsymbol{w}_i,\boldsymbol{w}_j)-\rho(\boldsymbol{W}))^2\Big/\rho(\boldsymbol{W})}+\sum_{t=1}^{m}\sum_{r=1}^{n}\boldsymbol{w}_{tr}\ln\boldsymbol{w}_{tr}$$

约束条件：

$$\bar{w}_r^{*}=\frac{\sum_{t=1}^{m}\boldsymbol{w}_t^{*}\boldsymbol{w}_{tr}}{m};\boldsymbol{w}_t^{*}=\frac{\rho_{tt}(\boldsymbol{w}_t,\boldsymbol{w}_t)}{\sum_{h=1}^{m}\rho_{th}(\boldsymbol{w}_t,\boldsymbol{w}_h)};\sum_{r=1}^{n}\boldsymbol{w}_{tr}=1,$$

$$w_{tr}\geqslant 0;\bar{w}^{*}=\frac{\sum_{t=1}^{m}\boldsymbol{w}_t^{*}\boldsymbol{w}_{tr}\bar{\boldsymbol{w}}_r}{m};r=1,2,\cdots,n;t(h)=1,2,\cdots m;$$

其中：$\boldsymbol{W}=\{w^1,w^2,\cdots,w^t,\cdots,w^m\}$；$\boldsymbol{w}_t=(w_{t1},w_{t2},\cdots,w_{tr},\cdots,w_{tn})$；$\bar{w}_r^{*}$ 是项目可持续影响因素的最终权重值. 归一化后就是基础设施可持续性影响因素的一般性权重. w_{tr} 表示第 t 个项目第 r 个可持续性影响因素的权重值，也就是 w_t 的第 r 个矢量分量，所有数值均标准化后取值.

3　基础设施可持续性影响因素权重确定步骤

步骤 1：单个项目可持续性影响因素结构分析.

首先，运用式(1)求出两两可持续性影响因素之间的关联度 $r_{ij}(v_i,v_j)$，得到 $n\times n$ 的关联度矩阵；然后，基于可持续关联度矩阵，对可持续性影响因素群体 $\boldsymbol{\Omega}$ 应用改进的矢量空间聚类方法进行聚类[17]，可以形成 p 个可持续性影响因素集 $\boldsymbol{\Omega}=\{C_1,C_2,\cdots,C_p\}$.

步骤 2：项目不同阶段可持续性影响因素初始权重确定

求出可持续性影响因素集间的关联度 $R_{ij}(C_i,C_j)$. 最后，影响因素 V_i 的权重 k_i 可以由 $r_{ii}\div\sum_{j=1}^{n}r_{ij}$ 算出，聚集 C_i 的权重 K_i 可由 $R_{ii}\div\sum_{l=1}^{P}R_{il}$ 确定[11]. 归一化后，运用影响因素集的权重和影响因素集中各个可持续影响因素的权重得出可持续性影响因素的初始权重为 $w_i=K_i\cdot k_i$. 将该权重按照表 1 中用二级指标重新排序得到单个项目可持续性影响因素的初始权重矢量为：$\boldsymbol{w}_t=(w_{t1},w_{t2},\cdots,w_{tn})$. 该权重大小反映了单个项目各可持续性影响因素对基础设施可持续性的影响程度. 运用 Matlab 软件将权重最优化模型(7)编程，计算初始权重矩阵的 $F(\boldsymbol{W})$，$f(\boldsymbol{W})$，$H(\boldsymbol{W})$.

步骤 3：可持续性影响因素权重初次优化结果

通过步骤 2 中方法，求解出单个项目在项目群体中所占的权重矢量，形成多项目权重矩阵 $\boldsymbol{W}=\{w_1,w_2,\cdots,w_t,\cdots,w_m\}$. 由模型(7)约束条件中的第 2 式可以求出项目可持续性影响在整个项目全生命周期中所占的权重为 $W^{*}=\{w_1^{*},w_2^{*},\cdots,w_m^{*}\}$.

以此权重矢量构造的对角修正矩阵左乘初始权重矩阵，得到初步优化后的权重矩阵. 从而，初次优化后的指标综合权重为：$\bar{W}=(\bar{w}_1,\bar{w}_2,\bar{w}_3,\cdots,\bar{w}_n)$.

步骤 4：可持续性影响因素权重再次优化结果

在初次优化的基础上，运用初次优化后的指标综合权重构造权重修正对角矩阵，对初次优化权重矩阵进行右乘，从而得到再次优化后的指标综合权重：$\bar{W}^{*}=(\bar{w}_1{}^{*},\bar{w}_2{}^{*},\cdots,\bar{w}_n{}^{*})$. 通过权重最优化模型(7)计算再次优化矩阵的 $F(\bar{W}^{*})$，$f(\bar{W}^{*})$，$H(\bar{W}^{*})$，将其与 $F(W)$，$f(W)$，$H(W)$比较.

步骤 5：可持续性影响因素权重迭代优化

继续对所得权重矩阵进行优化，直到当$F(W^{Z*})$趋近于某个极值最小值或者在某次优化后取得最小值时，取此时的极限权重$\bar{W}^{Z*}=(\bar{w}_1{}^{Z*},\bar{w}_2{}^{Z*},\bar{w}_3{}^{Z*},\cdots,\bar{w}_n{}^{Z*})$为最优权重.

4　实证分析

本文通过对 24 个真实的公路项目的跟踪与调查，并结合其环境评估报告、运营车流量、收费标准、公里数、运营成本等相关数据，计算和统计了表 1 中的基础设施可持续性影响因素的 27 个量化指标，即量化指标的真实值. 而影响因素量化指标的标准值则来源于历史数据的最优值或理想状态下的取值，差异值表示理想值与真实值之间的差距. 最终的基础设施影响因素量化指标真实值、理想值和差异值见表 2.(因篇幅所限仅列出联兴阿城项目的计算结果).

根据计算单个项目可持续性影响因素之间的关联度值进行聚类，聚类结果见表 3，从而得出联兴阿

城项目各因素权重见表 4. 以同样的计算步骤,可得出 24 个项目的可持续性影响因素权重见表 5.

表 2 联兴阿城段公路项目可持续性影响因素量化指标的真实值、理想值和差异值

Tab.2 The true, ideal and difference values of quantitative indexes of sustainability factors of Lian-A highway project

二级指标	量化指标值(v_{il}, $\bar{v}_{il}$, p_{il})
v_{1l}投资资金合理性	v_{11}年成本占总投资比例(0.055,0,0.055) v_{12}年收益占总投资比例(0.35,1,0.65) v_{13}内部收益率(0.111,1,0.899)
v_{2l}环保投资力度	v_{21}环保投资与总投资比例(0.018,0.05,0.646)
v_{3l}投资回收周期	v_{31}投资回收周期时间(18.2,1,17.2)
v_{4l}项目带来的经济效益	v_{41}经济效益费用比(1.42,5,0.284)
v_{5l}为经济发展提供便利设施	v_{51}增加辅助设施数量(1,10,0.1) v_{52}需求/供给(0.81,1,0.29)
v_{6l}对公众的影响程度	v_{61}征地面积占比(0.999,0.734,1.36) v_{62}拆迁面积占比(0.001,0.234,0.033)
v_{7l}公众满意度	v_{71}公众满意度比例(0.95,1.00,0)
v_{8l}自然生态影响	v_{81} 耕地占用(0.424,0,1.177) v_{82}林地占用(0.001,0,0.005) v_{83}生物多样性(3,0,1.846) v_{84}填挖平衡率(0.18,1,0.82)
v_{9l}水环境影响	v_{91}PH 值(4.69,7,0,33) v_{92}悬浮物含量(144,0,0.96) v_{93}生物需氧量(3.8,0,0.95) v_{94}重铬酸盐指数(2.5,0,0.83) v_{95}石油类(0.01,0,0.2) v_{96}氨氮(0.92,0,0.92)
v_{10l}大气环境影响	$v_{10,1}$N 二氧化氮(0.018,0.04,0.55) $v_{10,2}$施工微尘(300,0,1.317)
v_{11l}固体废弃物	$v_{11,1}$弃土渣方(3.74,0,0.028) $v_{11,2}$废物(21.6,0,0.298)
v_{12l}声环境影响	$v_{12,1}$影响距离(300,0,2.589)
v_{13l}环保措施	$v_{13,1}$环保措施严格落实比(0.95,1.00,0)

表 3 联兴阿城段公路项目可持续性影响因素聚类结果

Tab.3 Cluster results of sustainability factors of Lian-A highway project

聚集	可持续性影响因素	具体可持续影响因素
C_1	v_{1l}	建设资金合理性
C_2	v_{10l} v_{11l} v_{12l}	大气环境影响,固体废弃物,声环境影响
C_3	v_{2l} v_{3l} v_{6l} v_{8l}	环保投资力度,投资回收周期,对公众的影响程度,自然生态影响
C_4	v_{4l} v_{5l} v_{7l} $v_{9l}$$v_{13l}$	项目带来的经济效益,为经济发展提供便利设施,水环境影响,环保措施

在以上结果的基础上,以 24 个项目为群体 $\boldsymbol{\Psi}$,以上一步中得到的指标为准则,运用迭代的方法,按照 4 个步骤进行计算,优化前 $F(\boldsymbol{W})=223.543$,经过初次优化和再次优化后 $F^*(\boldsymbol{W})=1.229$.

多次优化后 $F(\boldsymbol{W})_{\min}=-10.521$,多次循环优化都是趋近于这个最小值. 因此求解得到在 $F(\boldsymbol{W})$最小情况下得到的基础设施可持续性影响因素的最优权重见表 6.

综合上述:(1)影响因素指标权重优化后相比优化前,$F(\boldsymbol{W})$大幅度下降,从 223.543 到−10,521,相对偏差也大幅减小,验证了基于关联度的多属性群体决策模型的有效性;(2)得到了 24 个公路项目的可持续性评价指标的一般性权重. 其中,对公众的影响程度、公众满意度、大气环境影响、固体废弃物、为经济发展提供便利设施等因素所占权重较大,分别

表 4 联兴阿城段公路项目可持续性影响因素的权重

Tab.4 The Weight of sustainability factors of Lian-A highway project

聚集	可持续性影响因素	可持续性影响因素集内权重	综合权重
C_1	v_{11}建设资金合理性	0.085 66	0.085 66
C2	v_{101}大气环境影响	0.324 03	0.072 89
	v_{111}固体废弃物	0.397 43	0.089 40
	v_{121}声环境影响	0.278 54	0.062 66
C3	v_{21}环保投资力度	0.231 13	0.069 79
	v_{31}投资回收周期	0.207 53	0.062 66
	v_{61}对公众的影响程度	0.305 21	0.092 15
	v_{81}自然生态影响	0.256 13	0.077 34
C4	v_{41}项目带来的经济效益	0.193 95	0.075 15
	v_{51}为经济发展提供便利设施	0.256 42	0.099 35
	v_{71}公众满意度	0.215 26	0.083 40
	v_{91}水环境影响	0.119 10	0.046 15
	v_{131}环保措施	0.215 26	0.083 40

表 5　24 个项目的可持续性影响因素权重表

Tab.5　The weight of sustainability factors of 24 road projects

项目名称	单项目可持续性影响因素权重
西安至铜川高速路	(0.059,0.078,0.073,0.074,0.103,0.076,0.077,0.104,0.054,0.078,0.073,0.073,0.077)
上林至马山二级公路	(0.051,0.073,0.072,0.075,0.064,0.093,0.069,0.092,0.046,0.149,0.069,0.074,0.073)
上海盈港东至崧泽公路	(0.062,0.077,0.077,0.078,0.063,0.077,0.077,0.077,0.073,0.100,0.080,0.078,0.078)
温州市快速公交一号线	(0.058,0.083,0.087,0.081,0.075,0.063,0.088,0.084,0.050,0.075,0.086,0.083,0.087)
万盛至綦江梨园坝公路	(0.060,0.086,0.085,0.086,0.072,0.103,0.089,0.028,0.049,0.085,0.087,0.086,0.086)
临安至杭州公路	(0.051,0.077,0.077,0.079,0.073,0.114,0.085,0.043,0.060,0.101,0.085,0.077,0.077)
界阜蚌高速路	(0.063,0.084,0.086,0.085,0.083,0.065,0.088,0.082,0.04,0.062,0.089,0.083,0.084)
联兴至阿城公路	(0.086,0.070,0.063,0.075,0.099,0.092,0.083,0.077,0.046,0.073,0.089,0.063,0.083)
绩溪黄山高速路	(0.052,0.081,0.078,0.080,0.074,0.113,0.084,0.071,0.062,0.058,0.083,0.079,0.083)
七台河至鸡西高速路	(0.059,0.088,0.083,0.081,0.068,0.081,0.082,0.079,0.044,0.080,0.084,0.084,0.087)
青冈至兰西高速路	(0.06,0.078,0.075,0.081,0.074,0.093,0.089,0.066,0.044,0.089,0.088,0.075,0.089)
泗洪许昌高速路	(0.054,0.079,0.077,0.079,0.074,0.093,0.082,0.074,0.071,0.076,0.084,0.076,0.081)
重庆江津至四川合江高速路	(0.053,0.079,0.082,0.082,0.088,0.083,0.093,0.060,0.041,0.079,0.092,0.084,0.085)
荆岳长江公路大桥	(0.054,0.079,0.080,0.080,0.072,0.067,0.089,0.089,0.074,0.070,0.080,0.080,0.086)
宁宣杭高速路	(0.063,0.083,0.081,0.081,0.083,0.058,0.083,0.091,0.056,0.073,0.083,0.083,0.083)
鹤大佳木斯至牡丹江高速路	(0.055,0.079,0.078,0.077,0.080,0.092,0.083,0.065,0.047,0.078,0.100,0.081,0.083,)
沈阳至吉林高速路	(0.049,0.077,0.075,0.080,0.096,0.094,0.085,0.081,0.054,0.075,0.072,0.080,0.082)
桂庙路快速化公路	(0.049,0.081,0.075,0.081,0.081,0.113,0.077,0.088,0.053,0.060,0.079,0.081,0.081)
龙城高速路	(0.049,0.074,0.073,0.086,0.078,0.105,0.092,0.067,0.038,0.073,0.081,0.091,0.092)
谢边至三堡高速	(0.050,0.072,0.065,0.070,0.076,0.210,0.082,0.056,0.037,0.061,0.0780,069,0.073)
大庆至肇源高速路	(0.057,0.082,0.082,0.082,0.085,0.081,0.084,0.068,0.052,0.082,0.080,0.082,0.084)
博罗至深圳高速路	(0.055,0.083,0.081,0.086,0.072,0.099,0.083,0.066,0.058,0.063,0.081,0.087,0.087)
广州至佛山城际	(0.054,0.077,0.076,0.077,0.078,0.093,0.082,0.077,0.071,0.079,0.082,0.077,0.080)
安康至陕川界高速路	(0.054,0.080,0.082,0.085,0.078,0.065,0.085,0.091,0.051,0.081,0.082,0.081,0.085)

表 6　基础设施可持续性影响因素的一般权重值

Tab. 6　Generalized weights infrastructure projects sustainability impact factors

一级指标	可持续性指标因素	一级指标权重	可持续性指标因素权重	综合权重
经济影响	v_{1l}建设资金合理性	0.281	0.201	0.057
	v_{2l}环保投资力度		0.269	0.076
	v_{3l}投资回收周期		0.258	0.073
	v_{4l}项目带来的经济效益		0.272	0.076
社会环境影响	v_{5l}为经济发展提供便利设施	0.282	0.279	0.079
	v_{6l}对公众的影响程度		0.431	0.121
	v_{7l}公众满意度		0.290	0.082
自然环境影响	v_{8l}自然生态影响	0.437	0.171	0.075
	v_{9l}水环境影响		0.109	0.048
	v_{10l}大气环境影响		0.187	0.082
	v_{11l}固体废弃物		0.182	0.080
	v_{12l}声环境影响		0.170	0.074
	v_{13l}环保措施		0.181	0.079

达 0.121、0.082、0.082、0.080、0.079，说明这些因素对公路项目可持续性的影响较大，在新建类似基础设施的项目时需重点考虑这些关键指标；(3)水环境的影响、建设资金合理性等因素所占权重相对较低，分别为 0.048 和 0.057. 水环境影响因素所占权重较低的原因在于公路的建设对水流、河流等影响较小，而建设资金合理性影响因素所占权重较低的原因在于，这些公路项目大都是政府出资建设，更为看重的是社会效益而非经济利益.

5　结论

本文构建的基于关联度的多属性群决策模型，为实现在影响因素和项目数量众多的情况下对基础设施可持续性进行评价提供有效的方法. 该模型通过修正系数矩阵对项目群体综合权重进行了优化，结合 24 个公路项目的实证分析验证了该模型的有效性. 该模型的优点在于评价所需数据来源于项目建设实际历史数据和运营状况相关数据，具有一定的客观性；且能适用于影响因素复杂，数量庞大的复杂系统的评价.

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