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Construction of project quality health monitoring system based on life-cycle theory

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Abstract: In order to more effectively assess the health status of a project, the monitoring indices in a project's life cycle are divided into quality index, cost index, time index, satisfaction index, and sustainable development index. Based on the feature of qualitative and quantitative indices combining, the PCA-PR (principal component analysis and pattern recognition) model is constructed. The model first analyzes the principal components of the life-cycle indices system constructed above, and picks up those principal component indices that can reflect the health status of a project at any time. Then the pattern recognition model is used to study these principal components, which means that the real time health status of the project can be divided into five lamps from a green lamp to a red one and the health status lamp of the project can be recognized by using the PR model and those principal components. Finally, the process is shown with a real example and a conclusion consistent with the actual situation is drawn. So the validity of the index system and the PCA-PR model can be confirmed.

Key words: life-cycle theory; principal component analysis (PCA); pattern recognition (PR); quality health monitoring

The health monitoring of projects is a complex project information management question. Monitoring goals may vary with different standards. Formerly established analysis models were mostly based on sole goal decision-making in individual project stages[1], such as quality control in the designing stage, quality control in the constructing stage, and cost control in the constructing stage. Although it may make the index structure processing more reasonable, it actually creates confusion of index transitions at different project stage interfaces and makes it unknowable whether the results of the formerly established analysis models are the most optimal solutions or not in a project's life-cycle. It also makes it difficult to form a unified analysis model of the health monitoring of a project in its life cycle. So the life-cycle theory becomes the inevitable choice of project health monitoring researches[2].

However, a project's construction and operation are dynamic processes, which leads to an instantaneous combination of different monitoring indices at any stage. And it may create a significant influence on the choice of project health monitoring. Thus how to integrate the index structure and how to choose a suitable model to screen the evaluation indices on the project health become the focal points.

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1 Selection of Project Health Monitoring Indices Based on Life-Cycle Theory[3-4]

In the life-cycle theory, the choice of indices of project health monitoring is to take a project as a coherent process of the organization's life cycle from the planning stages to the final abolition, which means that we should not fragmentally examine the series of indices during the whole process. Then the status of a project's quality of health can be inspected at any moment; also the project's historical and social responsibilities are brought into the scope of inspection. Thus, the concept of health is no longer confined to the technical scope but spreads to the rational scope in the project's life cycle. According to traditional theories as well as certain expansions, the indices that may come about in a project's life cycle can be divided into: 1) quality index; 2) cost index; 3) time index; 4) satisfaction index; 5) sustainable development index.

1.1 Quality index system

The quality index system is the series of indices which are to pursue the unity of the quality of work, the quality of the project and the overall functions of the end products or services and the indices, which focus on operations and bring out the value of the project's functions (see Tab. 1).

Tab. 1 The structure of the quality index system

The second level decomposition	The third level decomposition
Quality of design GQD	Designing standard GQD01
	Designing quality GQD02
	Technical standard GQD03
	Possibility of construction GQD04
Quality of construction GQC	Quality of material GQC01
	Quality of equipment GQC02
	Project quality system GQC03
	Quality of all subsections GQC04
	Quality of the entire project GQC05
Quality of operation GQO	Overall function GQO01
	Product or service quality GQO02
	Safety of operation GQO03
	Reliability of operation and service GQO04
	Maintainability GQO05

Notes: 1) Related indices also need to be further decomposed into various subsystems and various subsections; 2) The following tables are the same.

1.2 Cost index system

The cost index system includes not only the construction costs on the background of the traditional theoretical system, but also the operating costs in a project's entire life time[5]; the social costs of these problems such as staff health, project bidding, etc; and the environmental protection costs of the harmonious coexistence between the project and the environment (see Tab. 2).

Tab. 2 The structure of the cost index system

The second level decomposition	The third level decomposition
Cost in the life-cycle time GCC	Total investment in construction GCC01
	Operating costs GCC02
	Maintenance costs GCC03
	Investment in unit production capacity GCC04
	Social costs GCC05
	Environmental costs GCC06

1.3 Time index system

The time index system includes not only designing and service life time indices, but product market cycle time indices as well (see Tab. 3).

Tab. 3 The structure of the time index system

The second level decomposition	The third level decomposition
Project base time GTG	Construction period GTG01
	Payback period GTG02
	Maintenance or upgrading cycle time GTG03
Project life time GTE	Designing life time GTE01
	Physical service life time GTE02
	Economic service life time GTE03
Product market cycle time GTM	Market development period GTM01
	Peak period GTM02
	Decline period GTM03

1.4 Satisfaction index system

The satisfaction index system means how the ones surrounding the project appraise on the interests of their owns, such as users, investors, owners, contractors and suppliers, governors, producers (employees) and organizations (see Tab. 4).

Tab. 4 The structure of the satisfaction index system

The second level decomposition	The third level decomposition
Project users GPU	Prices of products or services GPU01
	Project safety GPU02
	Humanity of products or services GPU03
Project investors GPI	Investments GPI01
	Rate of return on the investment GPI02
	Possibility of reducing investment risk GPI03
Project owners GPO	Overall objectives of the project GPO01
Project contractors GPC	Project prices GPC01
	Construction time GPC02
	Corporate image GPC03
	Corporate relationships (or credibility) GPC04
Governors of project GPG	Prosperity and development in regional economy GPG01
	Increase of local financial GPG02
	Improvement in local images GPG03
	Prominent political achievements GPG04
	Employment and other social problems GPG05
Project producers GPP	Working environment (safety, comfort, humanity) GPP01
	Treatment GPP02
	Stability of the work GPP03
Organizations surrounding the project GPA	Protection of the environment GPA01
	Protection of landscape and heritage GPA02
	Job placement GPA03
	Demolition resettlement or compensation GPA04
	Building modeling, spatial harmony with the environment GPA05

1.5 Sustainable development index system

The sustainable development indices mainly focus on the project's influences on the ecological environment and resources and inspect the extents of their sustainable development (see Tab. 5).

2 Construction of the Evaluation Model

2.1 Model methods selection and the extent of its application

The model constructed in this paper is made up of two methods which are principal component analysis (PCA) and pattern recognition (PR) (called the PCA-PR model). In the entire project life cycle, there will be a great number of indices and data. Some of these data are quantitative indices but the others are qualitative ones. These two methods have their own attributes and functions. The PCA can pick up the key indices from all the monitoring ones and the PR can evaluate the quantitative and qualitative indices at the same time. Thus, these two methods are chosen to construct the aimed-at model.

Because of the evaluation indices for constructing the model, admittedly it is necessary to gather statistics and analyze the project's massive data, and this mission will cost many resources. So when the project's data are massive, the model can do its job. Thus it is evident that the model constructed here is suitable for large-scale projects.

2.2 Construction of the PCA-PR model

2.2.1 Principal component analysis[6-7]

1) Standardize (format) indices

Suppose that there are m indices, and the number of each index's observation values is n. Then we can create a matrix of observation values as follows:

$$\left.\begin{aligned} F_1 &= a_{11}x_1 + a_{21}x_2 + \ldots + a_{n1}x_n \\ F_2 &= a_{12}x_1 + a_{22}x_2 + \ldots + a_{n2}x_n \\ &\vdots \\ F_m &= a_{1m}x_1 + a_{2m}x_2 + \ldots + a_{nm}x_n \end{aligned}\right\} \tag{1}$$

Standardize the data of matrix $\boldsymbol{F} = [\boldsymbol{x}_1, \boldsymbol{x}_2, \ldots, \boldsymbol{x}_n]$, and obtain a standard matrix $\boldsymbol{F}' = [\boldsymbol{x}'_1, \boldsymbol{x}'_2, \ldots, \boldsymbol{x}'_n]$:

$$x'_{ij} = \frac{x_{ij} - \bar{x}_j}{\sqrt{s_j}} \tag{2}$$

where $\boldsymbol{x}_j = \{x_{1j}, x_{2j}, x_{3j}, \ldots, x_{ij}\}$, j is the j-th index, $i \in [1, n]$.

$$\bar{x}_j = \frac{1}{n}\sum_{i=1}^{n} x_{ij} \tag{3}$$

$$s_j = \frac{1}{n-1}\sum_{i=1}^{n}(x_{ij} - \bar{x}_j)^2 \tag{4}$$

2) Then we can obtain the correlation coefficient equation $\boldsymbol{R}(r_{ij})_{m\times n}$ of those standard indices by

$$r_{ij} = \frac{1}{n-1}\sum_{\alpha=1}^{n}(x_{\alpha i} - \bar{x}_i)(x_{\alpha j} - \bar{x}_j) \tag{5}$$

Tab. 5 The structure of sustainable development index system

The second level decomposition	The third level decomposition	The fourth level decomposition
Ecological environment GSE	Status of the influences on the environment GSE01	Emission amount and change rate of the exhaust gas GSE011
		Per capita emission GSE012
		Total emissions GSE013
		Three wastes treatment rate GSE014
		Influence of city noise GSE015
		Concentrations of atmospheric suspended particles GSE016
		Effluent waste of GNP unit GSE017
		Waste gas emission of GNP unit GSE018
		Emissions and sewage treatment rate GSE019
	Ecological indices GSE02	Water quality of major rivers GSE021
		Forest or green coverage area and per capita coverage area GSE022
		Area of soil erosion and rate of change GSE023
		Changes of the nature reserve areas GSE024
		Eligible degree of the drinking water GSE025
	Investments in environmental protection GSE03	Investment in environmental management GSE031
		Environmental protection investment and its proportion in GNP GSE032
Resource index GSR	Resource reservation GSR01	Natural resource reserves and its changing rate GSR011
		Extent of the development and utilization of resources GSR012
		Destruction or degradation of natural resources GSR013
	Resource consumption indices GSR02	Per capita resource amount of possession and consumption GSR021
		Rate of energy consumption growth GSR022
		Energy consumption per 10 000 yuan of output GSR023
		GNP units consumption of energy and water GSR024
		Amount of resources input GSR025
Sustainable development capacity of project their own GSS	Long-term adaption to the demands GSS01	Stability of project function GSS011
		Sustainability of project GSS012
		Maintainability of project GSS013
		Low-cost operation GSS014
	Project update and further development GSS02	Functional update GSS021
		Structural update GSS022
		Material update GSS023
	Ability of disaster prevention GSS03	Monitor and prediction GSS031
		Disaster defence GSS032
		Disaster loss size GSS033
		Emergency response GSS034
		Recovery and reconstruction GSS035

3) Seek the eigenvalues of the correlation coefficient equation $\boldsymbol{R}$:

By the characteristic equation $|\boldsymbol{R}-\lambda \boldsymbol{I}|=0$, we can obtain the eigenvalues of $\boldsymbol{R}$: $0 \leqslant \lambda_1 \leqslant \lambda_2 \leqslant \lambda_3 \ldots \leqslant \lambda_{n-1} \leqslant \lambda_n$. Their corresponding eigenvectors are $\boldsymbol{v}_1, \boldsymbol{v}_2, \boldsymbol{v}_3, \ldots, \boldsymbol{v}_m$.

And we call the α_k as the k-th contribution rate if α_k can be expressed as

$$\alpha_k = \frac{\lambda_k}{\sum_{i=1}^{n} \lambda_i} \tag{6}$$

where $\lambda_i (i=1, 2, \ldots, m)$ reflect the contribution rates of the principal components $F_i (i=1, 2, \ldots, m)$ to the information in the measured indices. Thus, the eigenvectors $\boldsymbol{v}_i = (v_{i1}, v_{i2}, \ldots, v_{in}) (i=1, 2, \ldots, m)$ reflect the contribution rates of the measured indices x_j to the principal components F_i. The rates are also equal to $\boldsymbol{a}_i = \{a_{i1}, a_{i2}, \ldots, a_{in}\}$ in the PCA model. It means that we should pick up those indices whose contribution rates to the principal components are small.

$$\lambda_m = \min(\lambda_i) \tag{7}$$

Then we can determine the principal component F_m which these indices correspond to.

Because we suppose that $\lambda_1 \leqslant \lambda_2 \leqslant \ldots \leqslant \lambda_m$, we should aim at F_1. When we inspect the eigenvector $\boldsymbol{v}_{1j}$ that F_1 corresponds to, we can pick out index $\boldsymbol{x}_j$ that the eigenvector $\boldsymbol{v}_{1j}$ corresponds to.

$$|\boldsymbol{v}_{1j}| = \max(|\boldsymbol{v}_{11}|, |\boldsymbol{v}_{12}|, \ldots, |\boldsymbol{v}_{1n}|) \tag{8}$$

This step is to screen out those indices whose contributions to F_1 are small. Suppose that the index screened out is χ_t. Then we use $n-1$ indices of χ_t to make up of a new matrix $\boldsymbol{A}$, and repeat Eqs. (1) to (8) until λ_1 is not so small. Thus, we finish screening out the indices. The process shown above is the so-called "principal component analysis".

2.2.2 Pattern recognition model[8]

The following steps show how we build the pattern recognition model:

1) Establishing the subsets of samples. The ideal standards of the indices are called as the fuzzy mode B in the life-cycle theory of a project's quality health. And all the

divisions of the entire project monitored are called as fuzzy objects A_i. Every subset of A_i, which is made up of the division projects' real-time data A_{ij}, is defined as the factor set.

2) Determining the factor set. The factor set referred to here is the quality healthy index sets which are classified artificially through the PMIS's inputting interface and then identified by the PCA model.

3) Quantifying the fuzzy subset. There are several methods available to quantify the fuzzy subset and to assure its membership values. Here we obtain some of the fuzzy subset membership functions and values by analyzing the statistical values[8] and determine the others by expert assessment and valuation (The methods of expert assessment and valuation mainly aim to deal with the indices that cannot be quantified).

4) Pattern recognition process. We suppose that the fuzzy set is $B \in \Gamma(n)$ and the given factors sets are $A_i (i = 1, 2, \ldots, n)$. If $(B, A_i) = \max\{(B, A_1), (B, A_2), \ldots, (B, A_n)\}$, then B is considered as the closest to A, and it is the so-called "the nearest principle".

There are several solutions to the nearest degree problem on the basis of different definitions, such as the hamming osculating method, the Euclidian approach degree, the measure close degree, the maximum-minimum closeness method. For example, the Euclidian approach degree is

$$N_i(B, A_i) = 1 - \frac{1}{\sqrt{n}} \left[\sum_{i=1}^{n} (A_i(\mu_i) - B(\mu_i))^2 \right]^{\frac{1}{2}} \tag{9}$$

where N_i is the nearest degree of the fuzzy mode B to the fuzzy object A_i, which shows the extent of closeness between every index set and the standard set.

3 Application Example

Here we use the data from a large palaestra project in a certain city, and show particularly how to use the PCA-PR model to analyze the project's quality health. The data presented here come from documents such as feasibility study reports, design reports, and completion inspection reports. For the convenience of research, we make some weighted processing on the second level decomposition indices through the consultations and investigations on all parties such as investors, owners, contractors, users, governors, and suppliers. The detailed data are shown in Tab. 6.

Tab. 6 The second level decomposition weighted indices on the quality health of project 10^{-2}

Part name	GQD	GQC	GQO	GCC	GTG	GTE	GTM	GPU	GPI	GPO	GPC	GPG	GPP	GPA	GSE	GSR	GSS
Central palaestra	0.73	6.55	0.82	8.25	5.25	1.78	1.83	1.13	1.25	1.30	0.55	1.21	1.37	1.29	5.11	2.67	2.49
Central gymnasium	0.57	5.45	0.78	4.75	4.35	1.22	1.17	0.50	0.75	0.81	0.30	0.42	0.71	0.72	2.63	1.41	1.63
Tennis centre	0.35	2.80	0.46	3.8	1.31	0.74	0.99	0.13	0.17	0.12	0.06	0.11	0.17	0.11	1.08	0.30	0.31
Indoor natatorium	0.35	3.20	0.44	3.2	2.09	0.76	1.01	0.24	0.33	0.27	0.09	0.26	0.25	0.31	1.18	0.62	0.57

3.1 Principal components analysis

1) Matrix $\boldsymbol{A}$ is made up of the indices from the data of Tab. 6. We can obtain the eigenvalue λ_i of the correlation coefficient matrix $\boldsymbol{R}$ by Eqs. (4) and (5): $\lambda_i = (-9.435 \times 10^{-16}, 4.3352, -3.1094 \times 10^{-16}, 5.7265, 4.6857, 0.2432, 0.2899, 1.3890, 1.6237, 0.9934, 0.7648, 3.6394, 0.0013, 1.1343, 3.1121, 0.3975, 1.0034)$.

2) Using Eqs. (7) and (8), we can obtain a new index system including nine indices, which are: 1) Quality of construction (GQC); 2) Cost in the life-cycle time (GCC); 3) Project base time (GTG); 4) Project users' satisfaction (GPU); 5) Project investors' satisfaction (GPI); 6) Project governors' satisfaction (GPG); 7) Organizations surrounding the project (GPA); 8) Ecological environment (GSE); 9) Sustainable development capacity (GSS). It means that we can use these nine indices to monitor the quality health of the project at the time of completion.

3.2 Pattern recognition

According to the model of the PCA in section 3.1 and the expert assessment law and the F statistics law, we can identify five corresponding states represented by standard objects $B_{1\text{-}5}$. The green lamp represents that the project is currently in a healthy state and does not need any concern. The blue lamp represents that the project is in a relatively healthy state; that is to say, small parts of the project can be accepted after some rectifications. The yellow lamp represents that the project is in a state of sub-health, which needs some concern; it means that the project can be accepted after a certain proportion of rectification work has been performed. The orange lamp represents that the project is in a relatively unhealthy state, which requires much attention, namely, a large proportion of the project needs rectifications. And the red lamp represents that the project is currently in a seriously unhealthy state and needs surveillance and intensive concern from all parties, and many parts of the project need to be redone; even further operation of the project may have already become meaningless.

Here we use the example of the central palaestra to show the process of the pattern recognition:

1) Build up the table of membership values on project quality health, and obtain the domain of the factor set screened by the PCA model.

2) Use the fuzzy pattern B set-up in Tab. 7 and the indices data to assure the membership values of the corresponding factor set.

$$B_{\text{central palaestra}} = \{0.820, 1.000, 1.000, 1.000, 1.000, 1.000, 1.000, 0.822, 1.000\}$$

3) Obtain the nearest degree of the domain U on the central palaestra by Eq. (10).

$$N(B, \text{I}) = 0.916, \quad N(B, \text{II}) = 0.809$$

$$N(B, \text{III}) = 0.729, \quad N(B, \text{IV}) = 0.534, \quad N(B, \text{V}) = 0.336$$

Tab. 7 Membership values of project quality health

Index name	Ⅰ Green	Ⅱ Blue	Ⅲ Yellow	Ⅳ Orange	Ⅴ Red
GQC	0.070, 1.0	0.065, 0.8	0.055, 0.7	0.050, 0.5	0.045, 0.3
GCC	0.080, 1.0	0.075, 0.8	0.070, 0.7	0.060, 0.5	0.050, 0.3
GTG	0.050, 1.0	0.045, 0.8	0.040, 0.7	0.035, 0.5	0.030, 0.3
GPU	0.010, 1.0	0.008, 0.8	0.006, 0.7	0.004, 0.5	0.002, 0.3
GPI	0.012, 1.0	0.010, 0.8	0.008, 0.7	0.006, 0.5	0.004, 0.3
GPG	0.012, 1.0	0.010, 0.8	0.008, 0.7	0.006, 0.5	0.004, 0.3
GPA	0.012, 1.0	0.010, 0.8	0.008, 0.7	0.006, 0.5	0.004, 0.3
GSE	0.060, 1.0	0.050, 0.8	0.045, 0.7	0.040, 0.5	0.035, 0.3
GSS	0.020, 1.0	0.018, 0.8	0.015, 0.7	0.010, 0.5	0.080, 0.3

According to the nearest principle: $(B, A_i) = \max\{(B, A_1), (B, A_2), \ldots, (B, A_n)\}$, it is easy to know that the quality health state of the central palaestra is the closest to the green lamp standard. That is to say, the state of the central palaestra is healthy at the time of completion.

We can also monitor the health of the central gymnasium, the tennis centre and the indoor natatorium by the PCA-PR method, which has been used to monitor the health of the central palaestra. The conclusion is that the states of the central gymnasium and the tennis centre are all closest to the green lamp standard, while the indoor natatorium is closest to the blue lamp standard. This conclusion is fully consistent with the actual results. Because of some construction problems as well as the sewage treatment problems, the indoor natatorium does not fully meet the green lamp standard. After some rectifications, it can be accepted.

4 Conclusion

Based on the life-cycle theory, the concept of project health becomes broader, which is not confined to the traditional concept used in former times. Therefore, a more scientific criterion or method is needed. Using the PCA-PR model, we can pick out the main indices that can truly indicate the health state of a project and quantify many experiential judgment criteria in order to accurately identify the health state of the project at any time point. So the model can help us avoid some embarrassing situations when we take a part as a whole in project monitoring, and, thus, it has strong practical value.

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基于全寿命周期理论的工程项目健康检测体系构建

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摘要:为了更有效地对工程项目的健康状态做出全面准确的评估,将全寿命期下工程项目所有监测指标按质量指标、费用指标、时间指标、各方面满意度和可持续发展指标等加以划分.并且基于该指标体系定性与定量指标相结合的特征,构建了 PCA-PR 分析模型.该模型先对全寿命期指标体系进行主成分分析(PCA),从之前构建的全寿命期指标中甄选出一批可以作为工程项目健康检测分析的主要特征指标体系;再针对这些主要特征指标体系进行模式识别分析(PR),即通过将工程项目即时可能状态划分为绿灯至红灯 5 种状态,利用模式识别模型和项目主要特征指标识别出项目任意时点的健康状态.最后结合实例进行相关分析,得出与实际情况较为吻合的分析结果,验证了该指标体系和模型的有效性.

关键词:全寿命周期理论;主成分分析;模式识别;健康监测

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