A Health Performance and Cost Optimization Model for Sustainable Healthy Buildings

Oumjoong Oh¹, Jeeyoung Lim¹, Chaeyeon Lim² and Sunkuk Kim*³

¹Ph.D. Student, Department of Architectural Engineering, Kyung Hee University, South Korea
²Research Fellow, Department of Architectural Engineering, Kyung Hee University, South Korea
³Professor, Department of Architectural Engineering, Kyung Hee University, South Korea

Abstract

To construct a sustainable and healthy building, it is necessary to build a system capable of efficiently analyzing, assessing and managing health performance data over the life cycle of a building. To fulfill such needs, health-friendly resources database, life cycle health-performance tree, health performance evaluation and health management concepts were suggested. Such studies focused on health performance. Selecting building materials based only on their health performance while ignoring cost is likely to lead to not only rapid construction cost increases, but also higher maintenance costs. For cost-benefit management, the health performance and cost management model was proposed. However, while the model can be used in decision-making, it is unable to suggest an optimization solution. To supplement this need, this study proposes a health performance and cost optimization model for sustainable healthy buildings. The model proposed here is composed of simulation and optimization modules for health performance and cost using the concepts mentioned above.

Keywords: health performance; health management; health-friendly resources; cost; optimization

1. Introduction

To construct a sustainable and healthy building, it is necessary to build a system capable of efficiently evaluating the health performance data of the resources needed (Jeong, 2000; Lee, 2005; Lee et al., 2013; Kim, 2012) and able to efficiently analyze, assess and manage the health performance of space through the building over its life cycle (Zheng et al., 2011; Lee et al., 2012a; Lee, 2007; Cho et al., 2010). However, previous studies have revolved around building performance evaluation limited to the specific building dimensions (Zheng, 2011; Todorovic, 2012; Lee et al., 2012b), as described through healthy building development theories (Lee, 2005; Cho, 2010), evaluation metrics (Yu, 2011), pollutant discharge by building materials (Huang and Haghighat, 2002) and indoor air quality (IAQ). To assess health performance in relation to these various dimensions, the concept of a health-friendly resources database (HRDB) (Lee et al., 2012b), life cycle health-performance tree (LHT) (Lee et al., 2012a), health performance evaluation (HPE) (Lee et al., 2013) and life cycle health management (LHM) (Lim et al., 2013a) were developed.

However, these studies revolved only around health performance. Selecting building materials based only on their health performance irrespective of cost is likely to lead not only to a rapid increase in construction costs, but also higher maintenance costs. As improving the health performance of a building requires cost input, it is impossible to improve health performance without cost increase. For cost-benefit management, a health performance and cost management model was proposed. However, while the model can be used in decision-making, it is unable to suggest an optimization solution regarding health performance and cost. To supplement this need, this study proposes a health performance and cost optimization model for sustainable healthy buildings. The model proposed here is composed of simulation and optimization modules for health performance and cost that are equipped with the concepts mentioned above. To achieve the objectives of this study, the following procedures were carried out. First, previous studies related to the HPE of buildings are reviewed. Second, the relationship between health performance and cost over the course of a building's life cycle are explained. Third, the health performance and cost optimization model developed to simultaneously evaluate health performance and cost is presented. Fourth, the model is verified through a case study.

*Contact Author: Sunkuk Kim, Professor, Kyung Hee University, 1732 Deogyeong-dearo, Giheung-gu, Yongin-si, Gyeonggi-do, 446-701, Korea Tel: +82-31-201-3685 Fax: +82-31-203-0089 E-mail: kimskuk@khu.ac.kr
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2. Preliminary Study

The indoor environment has been increasingly monitored since sick building syndrome was first identified. (MacNaughton et al., 2016) The Environmental Protection Agency (EPA) set out to characterize the indoor environmental quality in typical office buildings in the mid-90s through the Building Assessment Survey and Evaluation (BASE) study. They measured a wide array of environmental pollutants and building parameters in one hundred buildings in the U.S. (EPA, 1998) Spengler and Chen (2000), Lin and Mills (2001) and other researchers have conducted studies to quantify the indoor environment condition.

In the case of Korea, Shin and Han (2007) analyzed domestic and overseas green building certification systems, identified the evaluation indicators and determined that they fall short in social, economic and human points of evaluation and in consideration of regional characteristics, cultures and regulations. Lee et al. (2011) studied domestic and overseas green building certification systems to draw on evaluation indicators and conducted post occupancy evaluation to quantify each evaluation indicator. Lee et al. (2011) also pointed out the limitation that the results of a POE on only a few areas or occupants cannot fully represent all areas and occupants.

Most of the researches introduced above are related to the survey, analysis, classification and criteria establishment of an indoor environment mainly focused on indoor air quality, and do not provide for the overall health performance evaluation of buildings in an optimized manner. However, the LHA model is a system configured as described in Fig.1. to provide structure, information and a method for assessing the health performance of buildings and to enable users to share assessment results over the life cycle of buildings (Lim, 2013b). This chapter reviews other models developed in previous studies.

2.1 HRDB

The term HRDB refers to a database populated with analysis data for resources (materials, equipment and so on) currently available in the construction market. To build a HRDB, healthy building data were analyzed on the basis of literature review, sample data and data-gathering form considering basic details (specification, price and so on), then an interface to health performance metrics (light, heat, sound and air, among others) was designed. HRDB provides an environment in which environmentally friendly healthy building resource information can be integrated and shared over the life cycle of a healthy building (Lim, 2013b).

2.2 LHT

A LHT consists of four stages. Building information is divided by the LHT using space classification. Space classification can be divided again into block, floor, section and room depending on building type. Information classified by space is again divided into space configuration items (SCIs). SCIs can be further divided into combinations of materials, resources, services, openings, volume, shape and arrangement of space, depending on the space type. Health performance values corresponding to each and every SCI are calculated by quantifying and classifying each indicator. When the health performance calculated in this manner is summed, the health performance of the applicable unit space can be estimated. Each evaluation factor is associated with a different calculation method, even though they belong to a single health performance and the same is applicable to each health performance value. Therefore, aggregation of health performance should be classified and quantified using formula weights for each indicator (Lee, 2012a; Lim, 2013b).

2.3 HPE

LHT is a hierarchy and guideline for evaluating the health performance of a building. However, as is known from the LHT structure, measuring indicators for all SCIs and aggregating these data requires significant time and effort. From this perspective, Lee et al. (Lee, 2013) developed a computing model for determining the HPE of sustainable healthy buildings that adopted IT technologies for easy and quick application of health performance evaluation.

The HPE model iteratively evaluates the health performance of a space and shares evaluation results, using LHT and HRDB over the life cycle of buildings (planning, design, construction and O&M) (Lee, 2013). However, the HPE model evaluates only each phase and does not incorporate efforts to maintain health performance in comparison with preceding phases.

2.4 LHM

The purpose of a healthy building lies in providing a healthy space for residents and this purpose requires the health performance of a space to be quantitatively evaluated and managed. As described in Fig.2., the LHM model requires a minimum health performance, dubbed baseline health performance, to be maintained in a bid to ensure a comfortable living environment for residents. The model evaluated health performance at specific points in time, such as planning and design, to ensure that health performance is maintained (Lim, 2013a).
The criteria for health performance are set based on the owner's requirements and legal standards. When such criteria are established, the planning and design of buildings should conform to the set criteria and buildings should be constructed to have equivalent or better performance. When the health performance of buildings becomes lower than the set criteria, improvement through maintenance and repair should be done as various facilities and equipment age. The health performance of a building should be anticipated and maintained at or above a specified level in relation to its intended use over its life cycle. This effort is defined as LHM (Lim, 2013a).

However, the criteria for health performance can vary according to time as demonstrated in Fig.5. In particular, environmental standards for buildings will become stricter as the residents' standard of living and a nation's economy improve, which will lead to higher baseline health performance. For example, in Fig.2., health performance is maintained in the operation and maintenance phase, whereas minimum health performance is lower than baseline health performance. Fig.5. shows that baseline health performance increased at a specific point in the operation and maintenance phase. If such a baseline has not increased, a maintenance plan to improve the health performance of priority control targets will be established corresponding to the health performance level shown in Fig.5. However, as mentioned previously, when building environment standards become stricter in accordance with improvement of residents' standard of living and development of a nation's economy, baseline health performance may be increased. In this regard, the health performance of buildings requires LHM management.

2.5 Health Performance and Cost

The conventional LHA model does not reflect reality as it considers only health performance. As a construction project is required to work within a given budget, cost should be given consideration (Na et al., 2015). Na et al. (2015) defined the relationship between health performance and cost for each phase and then proposed a management model. In all life cycle phases, a project owner or its agent requires high health performance within a low project budget. Costs required for sustainable healthy buildings are not allowed to exceed the project budget and health performance is required to satisfy baseline values.

In each phase, the planner/designer/contractor maps out a plan for a sustainable healthy building by making decisions to meet the requirements of the project owner on the basis of various criteria, unit costs and SCI health data (Na et al., 2015). Fig.3. shows considerations required for making a building sustainable and healthy while satisfying cost and health performance (Lim et al., 2013b; Na et al., 2015). However, the study of Na et al. (2015) lacked concrete plans to manage the various influential factors shown in Fig.3. Furthermore, while the model can be used in decision-making, it is unable to suggest an optimization solution for health performance and cost.

2.5.1 Planning Phase

In the planning phase, planning documents are developed by a planner to reflect the project owner's opinion. The planner develops plans in reference to applicable standards and statutory requirements and on the basis of historical cost, health performance data and experience in a bid to satisfy the budgetary requirements and health performance level planned by the project owner. If the available budget is not sufficient for the health performance level required by the project owner, the planner should increase the project budget or persuade the project owner to lower the required health performance level (Lim et al., 2013b; Na et al., 2015).

2.5.2 Design Phase

In the design phase, the designer develops design documents to reflect the budget and health performance level requirements determined in the planning phase and using other project owner requirements. To ensure that details spelled out in design documents do not lead to cost overrun, the unit cost of each building SCI should be considered. Likewise, to satisfy the health performance level determined in the planning phase, the health performance data for each building SCI should be considered. If the construction costs of an applicable design exceed project budget or the estimated health performance level does not satisfy the planning phase requirements, re-design may be necessary (Na et al., 2015).
2.5.3 Construction Phase

In the construction phase, a contractor selects appropriate SCIs on the basis of planning and design information and then begins construction. As the construction phase requires the most cost within the life cycle of a building, it is important to keep the construction budget under control in order to avoid cost overrun. Depending on prevailing circumstances, a rise in material costs or technological development may lead to a change in construction costs and health performance level (Na et al., 2015).

2.5.4 Operation and Maintenance Phase

Aging of a building can aggravate health performance. Therefore, in the operation and maintenance (O&M) phase, efforts are required to maintain the health performance built in the construction phase at or above baseline by repairing and replacing finishing materials and services. In this phase, the O&M planner should also maintain health performance with a proper O&M plan using the available budget (Na et al., 2015).

As budget works as a constraint in all phases of the building life cycle, there tend to be different alternatives throughout the project and the contractor needs to compute and assess the cost and health performance of such alternatives in each phase.

3. Health Performance and Cost Optimization

3.1 Model Concept

Alternatives in each phase should be evaluated in terms of health performance and cost and then compared with each other. This research has developed a health performance and cost optimization model, which assesses whether different alternatives maintain health performance at or above an applicable baseline within the available budget. As described in Fig.4., the simulation model is composed of a DB, two methodologies and three modules.

Among these, HRDB as a DB, LHT and LHM as two methodologies were explained in Chapter 2. The three modules search for the optimum solution through mathematical calculation. The cost estimation module estimates the costs of SCIs determined in each phase. The HPE module evaluates the building health performance, utilizing SCIs determined in each phase and the project HRDB. This module is based on the HPE model developed by Lee et al. (2013) with the exclusion of the life cycle concept and reduction of scope to evaluation of building health performance. The simulation module compares and evaluates results produced by the two modules described above. When the calculated cost and health performance meet the requisite constraints, the simulation module finds an alternative that corresponds with an object function. The mathematical algorithm for these three modules will be described in detail in Section 3.2.

3.2 Mathematical Algorithms

As described above, the health performance and cost optimization model includes three modules. The cost estimation module and HPE module can function independently. The simulation module uses the results of the two remaining modules. The mathematical algorithm of each module is as follows.

3.2.1 Cost Estimation Module

To improve 2D-based cost estimation, for works that require excessive manpower and working hours, the construction industry has recently been using software (Lee et al., 2009). However, the software or algorithm is limited to a specific range depending on its use. The target for cost estimation related to health performance may be a whole building, or only a part of equipment facilities. Thus, a cost estimation module does not specify a mathematical equation or system and a typical cost estimation method is applied depending on the use model proposed in the study.

3.2.2 HPE Module

The HPE module herein uses Equations (1), which was presented in previous studies (Zheng et al., 2011; Lee et al., 2012a) and adopts the HPE model structure (Lee et al., 2013) to estimate health performance. According to the studies and literature, the health performance of a project is represented by the total health performance of spaces that compose the project studies (Zheng et al., 2011; Lee et al., 2012a). Here, the space refers to buildings, floors and housing units or rooms. The health performance of each space is again expressed by the sum of the health performance of each health factor study (Zheng et al., 2011; Lee et al., 2012a). Health factors are classified health performance areas like air, heat, noise and lighting among others. Health factors are sub-divided into evaluation factor studies (Lee et al., 2012a). For instance, the health factor of indoor air quality, is sub-divided into evaluation factors, including volatile organic compounds, formaldehyde, carbon dioxide concentration and so on (Lai et al., 2009; Yu and Kim, 2010). In other words, the health performance of a
A project could be defined as the total sum of health factors for all of the evaluation factors. However, since the measurement units and standards differ for each evaluation factor, health performance cannot be estimated by simply summing the variables. In this regard, Zheng et al. (2011) proposed a method of converting evaluation factors into health factors and health factors into health performance, as shown in Equation (1) through a fuzzy Delphi-analytic hierarchy process.

\[ \text{HP}_{pj} = \sum_{i=1}^{n} \sum_{j=1}^{k} W_{ij} \times \text{HP}_{ij} = \sum_{i=1}^{n} \sum_{j=1}^{k} W_{ij} \times \text{HP}_{ijk} \]  

3.2.3 Simulation Module

The simulation module compares and evaluates the results produced by the two modules described above. When the calculated cost and health performance meet the constraints, the simulation module finds an alternative that corresponds with an object function.

As described in Chapter 2, both the health performance and cost must be taken into consideration. Here, the project cost \( C_{pj} \) estimated by the cost estimation module cannot exceed the budget \( B_{pj} \) allocated to each applicable phase, as shown in the Equations (2). Health performance \( \text{HP}_{pj} \) of alternatives should be equal to or better than the baseline of health performance \( \text{HP}_{base} \), as shown in Equations (3). These conditions become the constraints of the optimization model. The purpose of this simulation module is to evaluate various alternatives and select the alternative featuring the best health performance at or above the baseline within budgetary constraints.

\[ C_{pj} \leq B_{pj} \]  

\[ \text{HP}_{pj} \geq \text{HP}_{base} \]  

The cost may increase when health performance is raised. However, it is anticipated that the rate of health performance improvement will gradually decrease as compared to cost as the health performance exceeds a certain level. Introducing environmentally-friendly materials and new technologies will result in dramatically increased cost. This is because the increasing efficiency against cost will decline as better materials or equipment are adopted. In other words, using the majority of the budget to optimize health performance may not be the best idea when balancing efficiency against investment. Thus, this study proposes the concept of value for health performance, as shown in Equations (4), to solve the optimization problem drawn above. Here, the value of health performance indicates the level of health performance against the cost invested, as shown in Equations (5).

\[ \text{Max} \left( \frac{\text{Value}_{HP}}{\text{Value}_{C}} \right) \]  

\[ \text{Value}_{HP} = \frac{\text{HP}_{pj}}{C_{pj}} \]  

3.3 Process Algorithm

Fig. 5 shows how to apply the health performance and cost optimization model developed herein. This simulation module analyzes the health performance and cost of multiple alternatives and selects an optimum alternative.

First, applicable alternatives are generated. The alternatives can be an alternative building design as a whole or specific to a single SCI. Alternatives for the whole building should be established if the whole building has to be optimized. However, a calculation of costs and health performance of such alternatives for the whole building for comparison requires a lot of time and effort. This optimization can be easy and fast if this model is systematized and automatized. This systematization and automation was studied by Lee et al. (2012b).

Second, alternatives are classified into SCIs by LHT. This was studied by Lee et al. (2012a). Information on materials combination can be classified into arrangement and opening, including material combinations and services; volume and shape can be classified into space information. As space components such as opening, space and services are difficult to convert directly to health performance, the health performance of each element can be analyzed to quantify the health performance.

Then, the health performance and cost of each SCI are computed using the HPE and cost estimation modules. Alternatives whose costs come within the given budgetary constraints and health performance at or above the applicable baseline are flagged. Then, the model finds the alternative with the highest value using the object function. However, either selecting an alternative requiring a minimum cost to ensure health performance at a certain level or ensuring the maximum health performance regardless of cost can be also viewed as optimization. This shall be studied further in the future.

4. Case Project

4.1 Brief Description of the Case Project

An example project is assumed, which has five ventilation system alternatives. The budget for the ventilation system is 135 thousand US dollars and the required health performance baseline for it is 40. The results of the cost estimation and HPE modules for all of the alternatives are described in Table 1. The project lifespan is assumed as 90 years. The total maintenance cost is calculated as the net present value (NPV) and the discount ratio for it is assumed as 2%.
In this case study, there are five alternatives. Among these, A4 was excluded because it was over budget according to the application of health performance and cost optimization models. The values of health performance for the remaining alternatives are described in Table 2. Herein, there are two kinds of value, initial value calculated only with initial cost and life cycle value calculated via initial cost and maintenance cost. Alternative A2 was noted as the best according to the cost-based life cycle health performance assessment model proposed by Lim et al. (2013b). However, it is the second-ranked alternative in the case of initial value and the worst alternative in the case of life cycle value according to the model proposed in this paper. On the other hand, alternative A1 is the best for initial value and A3 is the best for life cycle value.

In some cases, all alternatives may not satisfy Equations (2) and (3). In such a case, the manager should seek new alternatives, or request a greater budget from the owner based on justifiable reasons.

### Table 1. Health Performance and Cost of Alternatives

| Alternatives | Initial cost (thousand US dollars) | Maintenance cost | Total NPV (thousand US dollars) | Health performance |
|--------------|-----------------------------------|------------------|---------------------------------|--------------------|
| A1           | 120                               | 5                | 10                              | 80                 | 43                 |
| A2           | 126                               | 5                | 11                              | 88                 | 45                 |
| A3           | 133                               | 6                | 8                               | 53                 | 44                 |
| A4           | 140                               | 9                | 15                              | 64                 | 47                 |
| A5           | 123                               | 6                | 12                              | 79                 | 44                 |

### 5. Conclusion

HRDB (Lee et al., 2012b), LHT (Lee et al., 2012a), HPE (Lee et al., 2013) and LHM (Lim et al., 2013a) were developed and proved in previous studies. However, previous studies concerning health performance did not provide cost consideration. As improving the health performance of a building requires cost input, it is impossible to improve health performance without cost increase. Therefore, it is necessary to maintain the health performance of a building at or above baseline within the available budget. In this regard, this study proposes a health performance and cost optimization model for sustainable healthy buildings. The results of this study may be summarized as follows.

First, factors affecting health performance and cost in each life cycle phase of buildings were identified. Relationships between each influencing factor are described in Fig.3 and attributes and considerations of each life cycle phase were explained.

Second, a health performance and cost optimization model for a sustainable healthy building was proposed. The model proposed herein can keep building costs within the project budget and health performance at or above the baseline in each life cycle phase. A model concept was proposed and how to apply the model was explained.

Third, the best alternative was determined through virtual case application of the model proposed herein. The best alternative differed when using the proposed model and that proposed by Lim et al. (2013b). If the project owner gives more weight to cost than health performance, the A1 alternative derived by Lim et al. (2013b) is the best. However, the best alternatives upon considering health performance is A2 in the case of initial value and A3 in the case of life cycle value.

The health performance and cost optimization model proposed herein contains a simulation module to maximize the health performance value. If alternatives

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**Fig. 5. Health Performance and Cost Optimization Model**

**Table 2. Health Performance Value of the Remaining Alternatives**

| Alternatives | Initial value | Life cycle value |
|--------------|---------------|------------------|
| A1           | 0.358         | 0.215            |
| A2           | 0.357         | 0.210            |
| A3           | 0.331         | 0.237            |
| A5           | 0.355         | 0.217            |
are to be generated in simulation for all of the building design documents, this model requires a great deal of information and an enormous amount of time and effort for generating alternatives. Therefore, in reality, this model is expected to be used in supporting particular construction methods, such as value engineering or project decisions regarding specific parts of a project.

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