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Master of Science in Engineering

Decision Making Framework for Selecting Sustainable Construction Products

by

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February 2018

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A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Engineering

Seoul National University

2018

Decision Making Framework for Selecting Sustainable Construction Products

December 2017

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지도교수 박 문 서

이 논문을 공학석사 학위논문으로 제출함

2017년 12월

서울대학교 대학원

건 축 학 과

다르마라즈

다르마라즈의 공학석사 학위논문을 인준함

2017년 12월

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Abstract

Decision Making Framework for Selecting Sustainable Construction Products

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In construction industry, decision making plays an important role in achieving sustainability. Although decision making process and methods have significantly expanded to consider most product information when selecting a sustainable alternative to increase accuracy. The decision making process and methods itself has turned out to be a barrier due to knowledge intensiveness of the process and unreliable product information. This research focuses on developing a simple and transparent decision making framework for selecting sustainable product as alternatives.

Sustainable products are studied and previous researches on sustainable products are reviewed to identify the scope of the framework, criteria that needs to be considered and factors that would address the criteria in accordance with the research objectives.

The framework is developed comprising a decision making model that provides a visual comparison of the alternatives in consideration. Applicability study and case study of the framework provided insights on the issues with the framework and its limitations, along with being a validation step of the framework.

The resulted framework provides a distinct anticipated outcome description for each product considered, thus enabling the decision makers to identify the most suitable alternative. The applicability of the framework is expected to influence the spread of sustainable products globally in all scales of construction projects.

Keywords: Sustainable, Products, Decision, Framework, Risk, Obsolescence, Construction

Student Number: 2016-22083

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Chapter 1. Introduction

This chapter briefly introduces sustainable products and their significance to sustainable development in construction industry. Then, the chapter contemplates the developments of decision methods and their setbacks, which are preventing the spread of sustainable products globally. Problems relative to the decision-making methods that are causing the setback are established and the research objective is set to solve it. Additionally, the steps involved to attain the objective is provided in the research process section.

1.1 Research Background

Construction industry is responsible for a number of global environmental degradation including, 23% of all air quality pollution, 50% of CFC gas production, 40% of water pollution, 50% of landfill waste generation, 50% of ozone depletion, 80% agricultural land loss, 50% of coral reef destruction and 25% of rainforest destruction (Dixon 2010). A significant amount of these negative impacts is caused by the products used in the construction industry. As reported by Kleiwerks (2011), around three billion tons of raw materials are used to manufacture building products worldwide annually, which is 40-50 percentage of the total material flow in the global economy. In order to address this issue, sustainable products are produced as an alternative to almost all the products used in the construction industry (Spiegel et al. 2011). Sustainable products are those products that generate greater positive or lower negative social, environmental and economic impacts along the value chain from producer to end user than conventional products (Dufey 2005).

Although adopting sustainable products in construction industry is being identified as the easiest way for sustainable development (Akadiri et al. 2012), the selection of sustainable products as alternatives is found out to be one of the most difficult tasks in the construction industry (Kibert 2016). A recent research on the factors affecting the selection of sustainable materials suggest that the perception of extra cost being incurred and the lack of sustainable material information are the top barriers to sustainable material selection (Akadiri 2015), while cost is being dealt with life cycle costing (LCC) approaches to justify the initial investments being compensated with savings and returns on the long run, the lack of sustainable material information and the reliability of the information that being provided is a major setback for the decision makers to select the sustainable product as an alternative (Akadiri et al. 2012; Kang et al. 2009; Kibert 2016; Lerma et al. 2013; Prakash et al. 2013; Williams et al. 2007). Even though, there are over 460 environmental labels worldwide (www.ecolabelindex.com), reports shows that only 6% of EU citizens trust producers' claims about their products' environmental performance completely (Eurobarometer 2009). This kind of reliability issue exist because most of these labels are developed by third party organizations such as NGOs or collaboration of different organization with little or no government involvement in these labelling processes. With global sustainability standards still under development, there is major concern for reliability of these data. This raise an issue of data transparency provided by the seller, in terms of being able to cross-verify the data. The uncertainties existing with products of this kind requires evaluation to achieve realistic and transparent results of the product (Dangana 2013), but time and budget constraint hinders the testing of new products and systems before application (Ozorhon 2015).

Despite the fact that most modern methods of decision making are dependent on these data, they also require additional knowledge about various sustainable products, softwares and product evaluation methods, ideally increasing the complexity to make decisions from numerous new decision criteria (Dangana 2013). This prevents construction industry from adopting green practices especially in developing nations like India (M-Brain 2010). A major threat causing this is that small and medium contractors do not have the wherewithal to upgrade their capability (NSDC report 2017), which leads to a condition called knowledge gap between the large, medium and small-scale firms. The knowledge gap hypothesis explains that knowledge, like other forms of wealth, is often differentially distributed throughout a social system (Schumann 2007). The knowledge gap in this context is referred to the difference in knowledge about various sustainable products, softwares and product evaluation methods between different scales of the industry. Having around 30,000 small-scale firms and over 500 medium scale firms and 120,000 unregistered standalone contractors compared to only 250 large firms in India

(NSDC report 2017), it is important to consider this knowledge gap to provide solutions to make decision. This condition does not exclude developed nations either, as small and medium size enterprises (SMEs) in developed countries face the same challenges.

1.2 Problem Statement

In summary, rapid growth of the product market and lack of global standards for sustainable products have affected the reliability of the factors used in decision considerations, which also successively affects the results of modern product selection methods.

Added features and considerations of factors from "Cradle to Grave" of sustainable products have significantly increased the complexity of product selection methods in comparison with the traditionally used methods. Thus preventing the spread of sustainable products especially in SME due to the growing knowledge gap.

Therefore, to enable the spread of sustainable products especially in SME′s, it is important to provide a decision making framework that demands very little knowledge on the products and processes, while using reliable factors.

1.3 Research Objectives and Scope

Although previous studies develop methods that provide choices among alternatives, they lack the simplicity with their methods and lack transparency with the criteria and factors that they depend upon.

As an effort to address this issue, the objective of this research aims to develop simple decision making framework considering transparent factors for selecting sustainable products as alternatives in construction industry. The research focuses on identifying the least number of quantifiable factors that are collectively homogeneous to each individual product while being reliable to make decisions. Using those factors, a decision making model that provides a visual comparison of each alternatives and a description on the state of each alternatives is developed within the framework.

The scope of this research, considers all the sustainable alternatives used in the construction industry through which most generalized problems faced by the selection process are identified. Additionally, to provide an effective solution to these problems along with problems specific to a category of alternatives, the framework scope is defined to nonstructural sustainable products.

1.4 Research Process

This research follows a three-step process (as in Fig. 1.1), that starts with the preliminary study that would help to understand sustainable products and various decision methods that have been introduced to choose the alternatives. Additionally, this process would help to narrow down the scope to a specific subcategory of sustainable products. Lastly, this step provides the criteria, factors and process that aligns with the research objective, ideally providing all the knowledge required for the development of the decision making framework.

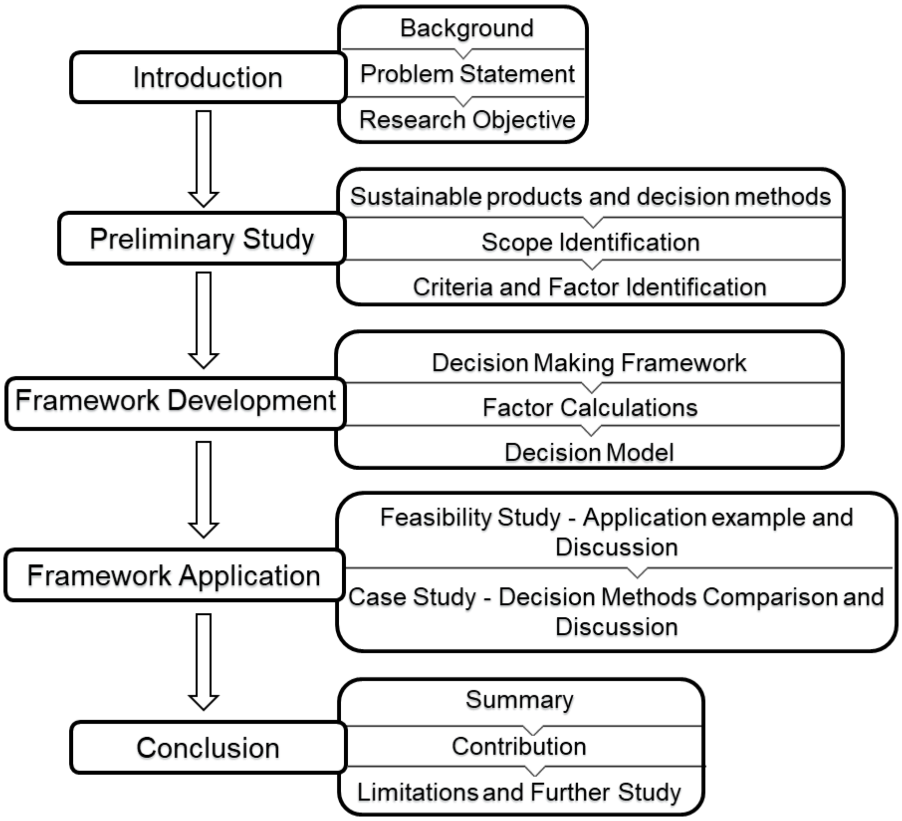


Figure 1.1. Research Framework

The second step includes the developed decision making framework and its process description. This step includes the methods to calculate the factors and then the steps involved on how the factors would be substituted in the model, followed by the model and its significance. The third step includes an applicability study on the framework and a case study as validation to the framework, followed by discussion and then conclusion. The conclusion includes a brief summary, contribution, limitations and further study.

Chapter 2. Preliminary Study

In order to develop the intended framework it is required to gain knowledge on existing methods. This chapter provides a brief introduction on sustainable products and its significance. Then, contemplates previous researches on sustainable product selection processes and methods used. Eventually, helping to provide a scope for the framework developed through this research. Based on the scope, the criteria that needs to be addressed when the decisions are made will be defined and the factors to address the criteria will be established.

2.1 Importance of Sustainable Products

The concept of sustainability in terms of demand for raw materials and its impact on the environment have been addressed and discussed throughout human history (Du Pisani 2006). According to UNESCO, sustainability is a paradigm for thinking about the future in which environmental, societal and economic considerations are balanced in the pursuit of an improved quality of life. Whereas, the processes and pathways to achieve sustainability is referred to as sustainable development. Selection of sustainable products is one such process to achieve sustainability. In order to understand the potential of sustainable products' influence in the construction industry, compare the fact that being a developed country, half of US's building stock required by 2050 is yet to be built, with the condition of developing countries where over 80% of global population lives (Kleiwerks 2011).

According to Leadership in Energy and Environmental Design (LEED), the green building process so far uses environmentally friendly materials that can save 250 metric tons of CO2 emissions annually (www.eesi.org). This provides a peak into the sustainable future of our planet with the help of replacing all the products into sustainable products.

Unlike green products, sustainable products used in construction industry are hard to be defined objectively. One of the reason is that they consider the impacts on the economic and social aspects along with the environmental aspects, while green products are products focusing on environmental aspects. Green products are defined as products that contain recycled materials, reduce waste, conserve energy or water, use less packaging, and reduce the amount of toxics disposed or consumed (Nimse et al. 2007). Although generalized, the research follows the definition of sustainable products by (Dufey 2005), defining it as those products that generate greater positive or lower negative social, environmental and economic impacts along the value chain from producer to end user than conventional products.

2.2 Existing Selection Process and Methods

Previous studies on selection of sustainable product are studied in order to understand the selection process of sustainable products and the methods used (refer Table 2.1).The studies included multiple decision making methods that are promising to provide highly accurate decisions. Life Cycle Assessment (LCA) (Hossaini et al. 2012; Lippiatt 1999) is once such method but detailed LCA is critically dependent on high volumes of product specific data and are often unaffordable (Srinivas 2007). Similarly, DNAP-TOPSIS (Govindhan et al. 2016) and Risk-Informed Decision Making (Lounis et al. 2016) methods also requires detailed knowledge and extensive data to make decisions. Additionally, hybrid methodologies such as Fuzzy extended AHP (Akadiri et al. 2013) requires knowledge on specific software tools to perform.

Multicriteria Decision Analysis (MCDA) (Dangana et al. 2013) methods are proof to provide simplified and transparent decisions to choose sustainable products. Choosing by advantages (CBA) (Arroyo et al. 2012; Parrish et al. 2009; Grant E. 2008; Nguyen et al. 2009) is one such MCDA method that has a very basic but promising logic of selecting the products based on the number of advantages, in the case of having reliable data. Lastly, Microsoft excel based method by Piotr et al. (2012) shows that minimalistic amount of support from modern software technologies could yield promising decisions.

Author	Decision for	Method Used	Evaluation Criteria/Factors	Scope	Observations
(Arroyo et al. 2012; Parrish et al. 2009; Grant 2008; Nguyen et al. 2009)	Sustainable Alternatives	Choosing by Advantage (CBA)	Product /component/system Specific	Comprehensive/undefined	Data intensive
(Dangana et al. 203)	Sustainable technology for retail buildings	Multi-Criteria Decision Analysis (MCDA)	Value Tree Developed	Limited/well defined	Simplified and Transparent
(Akadiri et al. 2013)	Sustainable materials for building projects	Fuzzy extended AHP (FEAHP)	Sustainable Triple bottom line based (TBL)	Comprehensive/ well defined	Knowledge intensive
(Lounis et al. 2016)	Sustainable and resilient infrastructures	Risk-Informed Decision Making	Product /component/system Specific	Comprehensive/undefined	Knowledge and data intensive
(Piotr et al. 2012)	Renewable/Sustainable Energy Systems	Microsoft Excel Based Application	Product /component/system Specific	Limited/well defined	Data intensive
(Hossaini et al. 2012)	Sustainable Materials	Emergy-Based Life Cycle Analysis (Em-LCA)	Product /component/system Specific	Comprehensive/undefined	Knowledge and data intensive
(Govindan et al. 2016)	Sustainable Materials	DNAP and TOPSIS	Product /component/system Specific	Comprehensive/undefined	Knowledge and data intensive
(Lippiatt 1999)	Green building products	LCA and LCC	Product /component/system Specific	Comprehensive/ well defined	Knowledge and data intensive

Table 2.1 Previous Researches on Decision Making for sustainable products

2.3 Nonstructural Sustainable Products

Additionally, 'the lack of comprehensive tools to compare material alternatives' is being an important barrier affecting selection of sustainable products in building projects (AlWaer et al. 2012; Bond 2011; Ikedasi et al. 2012; Akadiri 2015). Previous research have either provided decision methods for generalized sustainable product category or product specific methods. The generalized situation brings in the question of the effectiveness of such methods to all the products in scope. Whereas the product specific methods, demands the requirement of knowledge on multiple methods/criteria to cover a comprehensive set of products.

To provide an effective decision making framework, sustainable products are further subcategorized into structural and nonstructural sustainable products. Products that become or are part of the structural system are structural sustainable products (Griffen et al. 2010). While Singh et al. (2006) explains nonstructural products are the fixtures, attachments, and items in buildings and structures that are not designed as load bearing elements. By combining earlier definitions of sustainable product by Dufey and the definition of nonstructural products, nonstructural sustainable products can be defined as sustainable products that become or are part of a nonstructural component in buildings and structures. Nonstructural sustainable products includes architectural features such as exterior cladding and glazing, ornamentation, ceilings, interior partitions, and stairs; mechanical components and systems including air-conditioning equipment, ducts, elevators, escalators, pumps, and emergency generators; electrical components including transformers, switchgear, motor control centres, lighting, and raceways; fire protection systems including piping and tanks; and plumbing systems and components including piping, fixtures, and equipment" (Gillengerten 2001).

Although structural and nonstructural sustainable products face similar challenges for decision making from comparing their barriers to implementations from Griffen et al. (2010) and Akadiri (2015), failure of structural sustainable product to perform their intended function affects the integrity of the structure directly whereas that of nonstructural products are more indirect, which can be mitigated by repair or replacement of the product. Considering this intensity of risk involved, structural sustainable products are recommended to be chosen upon detailed evaluations using methods such as Lounis et al. (2016)'s Risk-Informed Decision Making. Moreover, the diversity of nonstructural sustainable products would resolve 'the lack of comprehensive tools to compare material alternatives' barrier that is affecting the selection of sustainable products by providing the necessary well-defined scope that could provide decision solutions for a comprehensive set of alternatives.

2.4 Decision Criteria-Economic Value, Obsolescence and Risk

In order to provide rational decision making to choose suitable alternative from sets of both sustainable and conventional products, suitable decision criteria that are specific to nonstructural sustainable products are identified. These criteria are selected based on their importance relevant to the decision makers and the current market situation of the products are taken into considerations.

Economic Value- Cost of sustainable products is prominently the most frequently cited barrier affecting the selection and use of sustainable materials (Akadari 2015), because the perception of extra cost being incurred is one of the most important barrier that affects the selection of sustainable materials (Aye 2003; Bond 2016; Samari et al. 2013; Williams et al. 2007). Considering, cost being the most important criteria, it is required to be justified in terms of economic value of the product from purchase to disposal/resale.

Obsolescence- Obsolescence occurs when products become “out of use” or “out of date” (Rahul Rai et al. 2008) A study on demands for private sector housing refurbishment concluded that obsolescence is found to be an overwhelmingly important basis for refurbishment than deterioration (Aikivuori 1996). The direct effect of product obsolescence is the tremendous amount of waste it generates (Rahul Rai et al. 2008). Obsolescence has been comprehensively addressed in the defence, aerospace, electronics and software sectors in over 60 research articles and with over 15 obsolescence management tools (Rojo et al. 2010), but not much considerations is given in the construction industry where the effect of obsolescence has been relatively low until recent times, which correlates to concern of the amount of waste generated by the construction industry. The sustainability perspective of the industry now has the need to consider obsolescence as decision criteria to uphold sustainability (Ofori 2012; Doloi 2012; Doherty 2002; Venegas et al. 1996).

Risk- Risk of "newness" is the risk of not meeting the technical requirements for performance or quality of output under the conditions of operations (Tatum 1989), either directly or indirectly affecting the economy and safety of the stakeholders. New products experience frequent malfunctions that should have been resolved before they were released into global markets (Makhlouf, et al. 2015). Observed in aerospace, automobile, electronics, and software industry, this risk of "infant mortality" in new products has increased in construction industry in the sustainable product market. Sustainable products are more prone to risk in comparison to conventional products with respect to the newness of the product being available in the market (Prakash et al. 2013).

The criteria under considerations are have certain interdependencies, such as obsolescence and risk of a product would affect the disposal/resale costs and maintenance costs of the product respectively, enabling them to be a balanced set of criteria to make decision based on.

2.5 Quantifying Factors of Decision Criteria

Factors that quantifies the decision criteria are identified as Life Cycle Cost (LCC) and Technology growth rate (TGR), which are selected in an effort to have the least number of homogeneous factors all the products, which are collectively unique to each alternatives, while containing disclosed information that are reliable. For example, no two products in the market offers the same life cycle cost while having the same technology growth rate.

Life Cycle Cost (LCC) is used to address economic value as it considers all the relevant economic factors, both in terms of initial capital cost and future operation costs (Norman 1990; Kirk et al. 1995; Woodward 1995; Gluch et al. 2004). Life Cycle Cost here considers all the costs involved from the decision maker's perspective that includes initial/capital cost of the product to the disposal/resale cost of the product. For example, selecting a highly energy efficient HVAC system over conventional HVAC system would infer high initial cost but considering the life cycle cost of the systems would prove that the energy efficient alternative has a better economic value over others. So, having LCC as the factor for economic value provides better justification in terms of the expenses incurred over the entire life of the products. LCC of a product is dependent on the local cost indexes as the calculation of future costs including operation and maintenance cost is calculated based on local cost data. This helps to provide more accurate region specific comparison of products.

Technology growth rate (TGR) is the factor to address obsolescence and risk. The growth rate of a products technology affects the chances of the product being obsolete (Bartels et al. 2012; Cooper 2016) and the uncertainty that comes with the product because of its "newness" (Charan et al. 2006; Makhlouf et al. 2015). Technology growth rate addressed here is the growth rate of the most advanced feature of the product specific to the company since the introduction of the product in the market. For example, consider window panels incorporated with transparent solar cells, which are relatively new in the market to existing window panel features and the capacity of power generation in these transparent solar cells, are increasing exponential with the rapid growth of technology in the field. This leads to the product available in the market today being obsolete within a short period. Similarly, because of the newness of such products, the risk of performance failure is high. TGR of a product is an independent company specific factor that would provide rational perspective of reputation specific to the product lineup and not the brand as the whole.

From the statements, the relation between the decision criteria and the factors can be interpreted as- economic value is inversely proportional to LCC; obsolescence and risks are directly proportional to TGR respectively, as obsolescence and risks are not correlated. Using quantitative factors (LCC and TGR) as an input, qualitative output (economic value, obsolescence, risks) of products relative to each other would provide the decision makers the necessary insights to choose suitable alternatives.

2.6 Four Quadrant Decision Making Model

The number of criteria and the factors addressing the criteria are reduced to the least possible quantities to provide a simple four-quadrant decision making model which can be used to make decisions for all nonstructural sustainable products. A simple four-quadrant model as shown in Fig. 2.1 would provide a simple and straightforward comparison between the alternatives. Four Quadrant model have been used in different fields for simple insightful decision making. Contrary to the trends of Multicriteria Decision Analysis (MCDA) methods and Machine Learning methods, using four quadrant model to make decisions is expected to significantly influence the spread of sustainable products, especially in developing countries among the small and medium enterprises.

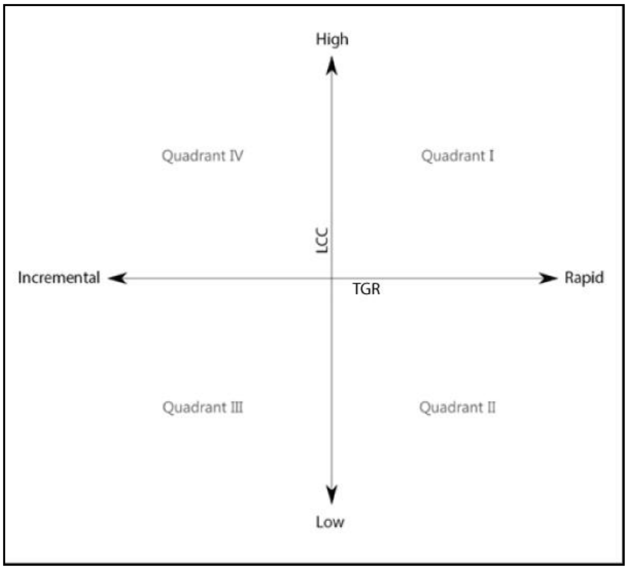


Figure 2.1. Simple Decision Making Model

2.7 Summary

Selecting sustainable products in construction industry have become the easiest way for sustainable development. The efforts of the previous researches have significantly improved the accuracy of product selection. However, the amount of knowledge and reliable data demanded by these researches is found to be overwhelming to use them globally. On the positive side, the researches provided useful insights for the framework to be developed. Through the study, non-structural sustainable products were chosen as scope of the framework in order to address a comprehensive set of products without the need of knowing multiple decision methods for different products. Then, Economic value, obsolescence and risk were identified as the criteria to be addressed when selecting nonstructural sustainable products as alternatives. In addition, the least number of homogeneous factors that are collectively unique to each alternatives were narrowed down. The factors are ‘life cycle cost’ addressing economic value of the product and ‘technology growth rate’ addressing obsolescence and risk. Reducing the factors addressing the criteria enables the development of four quadrant decision making model within the framework which is expected to influence the spread of sustainable products globally.

Chapter 3. Framework Development

By combining the knowledge gained from the preliminary study, this chapter attempts to develop a decision-making framework that stays true to the research objective and addressing the selection criteria through the factors chosen. Firstly, the research framework workflow is created and explained. Then, the formulas and method of factor calculation is established. Finally, the model that will be within the framework is developed and the significance of the model is explained. The entire framework is created with emphasis on being simple and using transparent factors that would be understandable and reliable even for the professionals with limited knowledge.

3.1 Framework Workflow

Based on Pearce et al. (1995) framework for selection of sustainable materials, the framework workflow is developed for this research as shown in Fig. 3.1. The process involves identifying the purpose of design element and then prepare minimum performance criteria to fulfil the design purpose. Then, a number of possible alternatives that fulfil the criteria are selected. All the infeasible alternatives due to various reasons such as design limitations, application limitations and others are pruned prior to the next set of evaluations. The shortlisted few alternates are then evaluated to find their LCC and technology growth rate values.

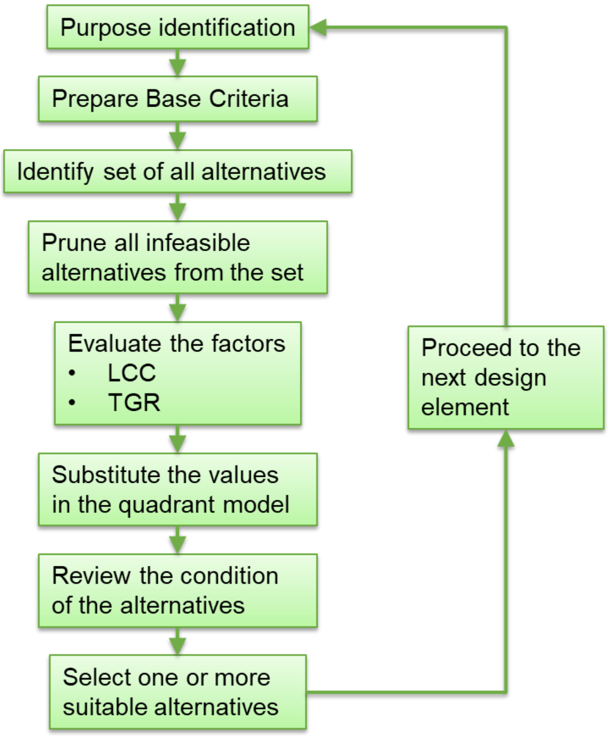


Figure 3.1 Framework workflow

3.2 Factor Calculations

Life Cycle Cost of the product is estimated by using the following formula (Eq. 1) adopted and simplified from Soni et al. (2014).

$$LCC = C_0 + PV\ (C_1 + C_2 + C_3 + C_4 - C_5). \qquad (1)$$

LCC - Life Cycle Cost, C_0- Initial capital costs, PV- Present values, C_1- Lifetime operating costs, C_2- Lifetime maintenance costs, C_3 - Capital rehabilitation costs, C_4 - Disposal costs, C_5 - residual value.

Considering the exclusive lifetime of the nonstructural products (Dangana 2012) from the building itself, cost such as operation cost and maintenance cost are calculated specific to the products life cycle, but would be repeated to meet the period of the buildings lifecycle or minimum required lifespan.

While, LCC formula is being constantly evolving to consider various criteria specific to products, facility, their impact among others are taken into considerations (Gluch et al. 2004), in order to provide LCC value based on data that is reliable and with least processing knowledge, the fundamental version of LCC calculation is selected to be used in the framework.

Technology growth rate of the most significant feature of the product is calculated by XY scatter plot of "feature vs time", inspired from Josais et al. (2009)'s paper on obsolescence risk assessment of computer components. TGR value is extracted using the exponential trendline function equation in Excel (Eq. 2):

$$Y = c * e \wedge b * x. \tag{2}$$

Where, Y= feature,

c= initial value,

e= exponential coefficient,

b= technology growth rate,

x= time.

The technology growth rate (b) of the product obtained in decimal form and converted into percentage. In case of newly released product in the market, the TGR value will be assumed and computed in the model as 100%.

The exponential growth rate function in Microsoft excel is used in finance to calculate the alteration in currency value, stock value and so on. Using it for calculating the growth rate of a products performance over a period would be a simple alternative over other methods.

3.3 Decision Model Integration

A four-quadrant decision making model is developed within the framework that provides a visual comparison of all the alternatives based on LCC and TGR values relative to each other. Description of the model and the significance of each quadrant are established. The visual aid of the model is expected to play a major role when comparing multiple products and to reason out with owners and investors, especially those who lacks professional knowledge on product selection.

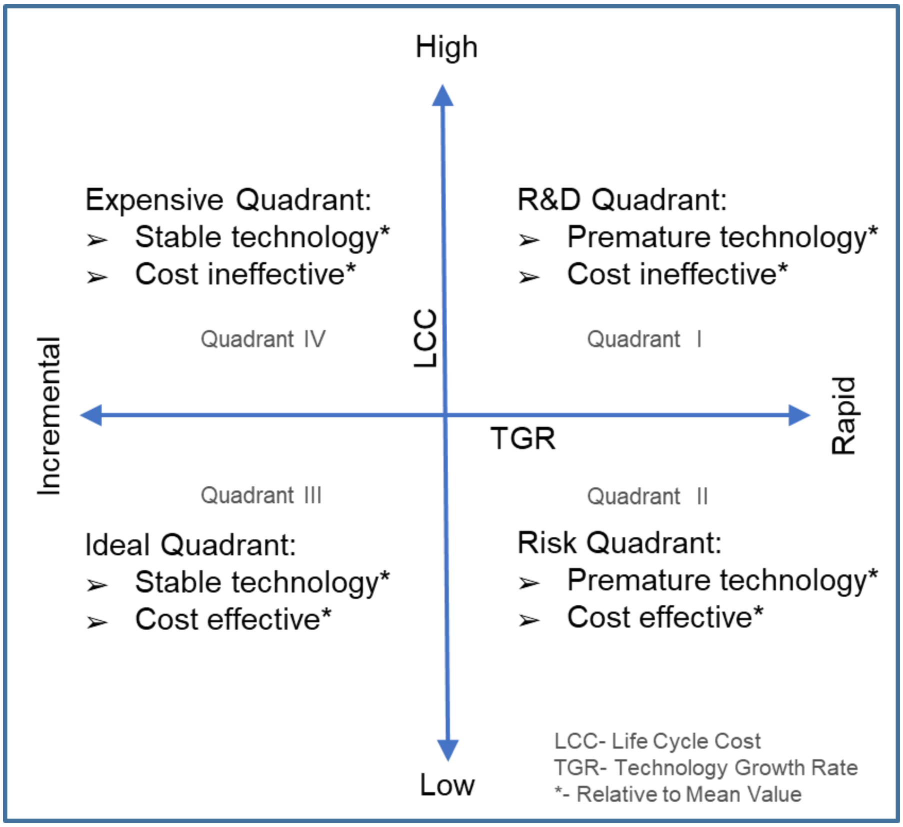


Figure 3.2 Four Quadrant Decision Model

Description- The Four-quadrant model consist of LCC in y-axis and TGR in x-axis as shown in Fig. 3.2. The base value (point of intersection of axis) is the mean value of LCC and TGR of all the alternatives. The values of LCC and TGR of each alternative are substituted in the four-quadrant model, with reference to the base value. The values of LCC are given to be in range of high to low and the values of the TGR - being rates were given in range of incremental to rapid, for better understanding of the model.

Quadrant significance-

'R&D Quadrant' has products with high LCC and rapid technology growth rate similar to prototypes that requires further research and testing before implementation. The quadrant emphasis that sustainability cannot be achieved by compromising on economic value and safety of the end-users. Moreover, product obsolescence would generate more waste and so the products in this quadrant are not recommended.

'Risk Quadrant' has products providing LCC savings on the long run using the latest of the technology available. Since these are prone to more risk and obsolescence relatively to common practices, products in this quadrant are recommended in partial combination and frequent inspection.

'Ideal Quadrant' has products with cost saving and mature technology that are ideal to implement and are highly recommended.

'Expensive Quadrant' has sustainable products are expensive at times even with a stable growth rate, due to the expenses of the manufacturing process, expense of the materials used in the products among others. Product with mature technology with little or no economic value relatively, are recommended only for requirements of regulations and certifications.

3.4 Summary

The Framework workflow included purpose identification of the design element, followed by the preparation of base criteria. The alternatives choses were then pruned according to the base criteria and then the LCC and TGR factors are calculated for each individual alternatives. Then, these values are substituted into the four-quadrant decision model. The model provides the necessary description to each alternatives relative to each other that would help the decision makers to make the decision.

Chapter 4. Framework Application

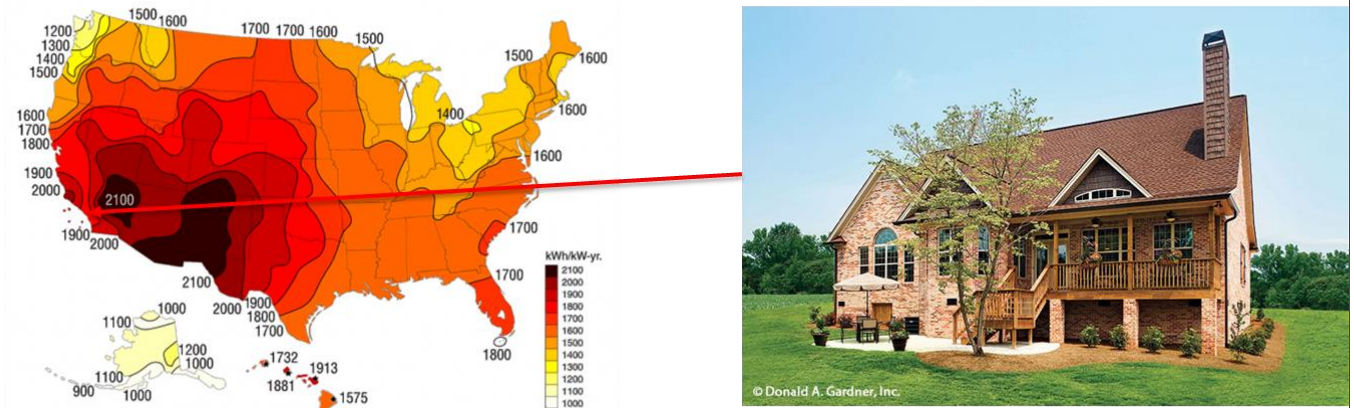
The framework is developed with the intention to be applied widely to influence the spread of sustainable products in all scales of the construction industry. To examine the working of the model and to understand its applicability in the industry a applicability study is performed to identify issues and limitation of the model and then a case study is performed to compare the methods currently used in the industry with the model.

4.1 Applicability Study

To examine the practicality of the model a simulated example of decision making to choose roof tiles for a new single-family house in San Diego, California is tested. The details of the sample project is provided in the Table 4.1 and Fig. 4.1 below.

Project characteristics	**Description**
Location	San Diego, California, US
Project Type	Single-Family House
Area	2,635 square foot (US Average as of 2016)*
Stakeholders	Owner, Architect, LEED Professional and General Contractor
Product	Roof Tiles/Shingles
Roof Area	3,430 square foot (average for 10/12 pitch=rise/span)**
Average solar energy generated by one kW system per year	1900kW (California-Average)
Climate	Mild and sunny weather throughout the year
*National Association of Home Builders Discusses Economics and Housing Policy **http://www.calculator.net/roofing-calculator	

Table 4.1 Sample Project Characteristics



National renewable energy laboratory-
solar energy generated per kW unit system per year

sample image

Figure 4.1 Sample Project

To provide sustainable solutions, the project characteristics are given importance to choose the most suitable option. In this case, based on the roof area exposed to sunlight and the average solar energy availability are important characteristics to include products that offer solar energy production features. Similarly, the products durability standards are need to be based on the local climatic conditions, as expensive, high standard and multiple featured products are not always the best choices.

After the assessment of the project characteristics, the selection process is followed according to the framework developed. The design element to install is the roof tiles/shingles and the purpose is identified as to provide sustainable weather protection. Based on this purpose and with due considerations given to the project characteristics, a set of performance criteria were set as conditions to be met before further review. Through this pruning method, the products are shortlisted as shown in Table 4.2.

Purpose	**Sustainable weather protection (Particularly heat insulation)**
Base Criteria	1. *At least one sustainable feature-* • Renewable energy generation, (LEED: 1-2, 1-3 Credits)* • Made from recycled materials, (LEED: 2-4 Credits)* • 100% recyclability, (LEED: 1 Credit)* • Energy saving by insulation (LEED: 1-2 Credits)* 2. *10/12 Pitch (slope steepness)*

	3. *<u>Fire Resistant</u>* • Best in Class Fire rating, equivalent to Class A UL 790** 4. *<u>Warranty</u>* • Functional warranty > 20yrs • Product warranty > 30yrs
Total no. of products considered	21
Shortlisted based on Base criteria	7
Shortlisted due to historical information shortage	4
*http://www.usgbc.org/ **http://library.ul.com/	

Table 4.2 Sample project framework workflow

Among twenty-one options considered initially, fourteen are pruned based on the base performance criteria and then three more are pruned due to the lack of historical data. The process brought down the number of alternatives to four. Then, the shortlisted products complete specifications were collected as shown in Table 4.4, from the product sources without prejudice. Unlike existing methods depending on the liability of these specifications for decision making, this method considers the growth of the performance of the most significant feature of the product by the seller. The technology growth rate of each product′s significant feature is calculated and the life cycle cost of each product is calculated using the local cost data standards (as shown in Appendix A) and computed in the model.

Specs\Company	Company 1	Company 2	Company 3	Company 4
Product Name	Slate	Single width Slate	Roof Slate	Solar roof
Material	Thermoplastic Olefin	polymer roofing	recycled thermo-plastics	Glass
Dimensions	18” X 12”	18” X 12”	18” X 12.5”	14” X 8.65”
Weight	725.748 g	843 g	750 g	-
Recyclability	100%	100%	100%	-
Energy saving	-	-	-	$98,900
Hail Rating	UL 2218 Class 4	UL 2218 Class 4	UL 2218 Class 4	Class 4 FM 4473
Wind Rating	ASTM D 3161	ASTM D 3161	UL 997	Class F ASTM D3161
Fire rating	Class A UL790	ASTM E 108 class A	Class A UL790	Class A UL 790
others	ASTM G21-09 ESR-3325 ASTM G155	-	AS/NZS – 4020 AS/NZS - 4046 AS/NZS - 2049	Glass coating ASTM C1376EN 1096
Product Warranty	50 yrs.	Limited lifetime	50 yrs.	Lifetime for tile/ 30 yrs. for power
Rough Capital cost including installations/square foot	8$/ sq. ft	9$ / sq.ft	11.12$ / sq.ft	20.29$ / sq. ft.

Table 4.4 Roof tile alternatives

4.2 Application Practicality Inferences

The following are inferred from the framework application. From the model (Fig. 4.2), Company 1- provides the recommended roofing option balancing cost effectiveness and stable technology relative to the other three

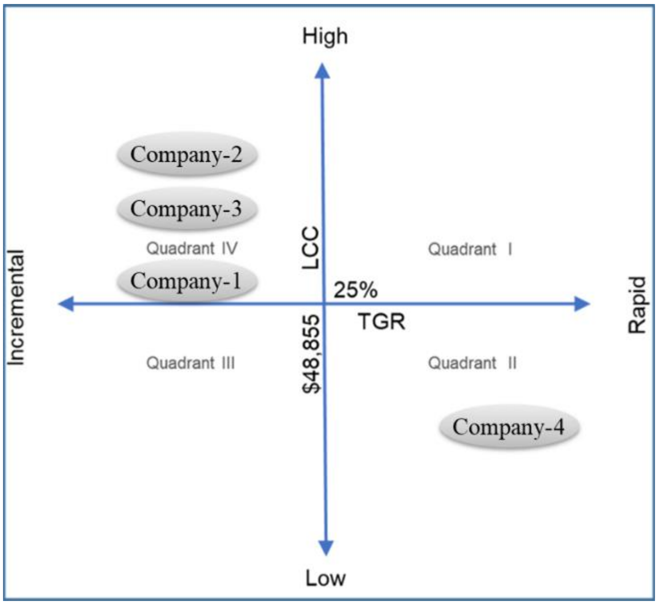


Figure 4.2 Sample project's decision model

options. Company 3- provides the second best option. Company 2- could have been an option when required LEED certification in the absence of products from Company 1 or Company 3. Company 4- provides the most economical option, but recommended only to be implemented partially with high caution and increased inspection frequency as it is considered to have more risk being a new product in the market. *Company 4-* Most economical option, but recommended only to be implemented partially with high caution and increased inspection frequency as it is considered to have more risk being a new product in the market.

Historical data of individual company's construction products are progressively developing but not readily available. The lack of linear data of products are also due to naming and introducing an advanced version of the same product into an entirely new line of products. LCC is calculated based rate assumptions and on standard local construction cost index values for maintenance cost, operation cost, residual and disposal values, and not product specific values. Significant advancement are more easily visible with products that contribute to energy saving/energy generation.

4.3 Case Study - Lighting fixtures in Multistorey Building Car parking facility

A case study is performed to compare the framework with existing selecting process in the industry. The case study involves the renovation of lighting fixtures for car parking facility of a multistorey building. The study is a part of major renovation performed by a major facility management firm in South Korea.

The purpose is identified as to provide sustainable lighting solution to obtain green certification. The base performance criteria was kept anonymous and the number of alternatives were brought down to two options, 'Alternative A' and 'Alternative B'. Alternative A – is to continue with existing lighting products (replacing with same new ones). Alternative B – replace with highly energy efficient LED lights. The choice of the company providing LED option was based the reputation of the company selling the product. The decision process included calculation of two quantities with respect to the products, LCC and CO_2 emission value of the products as shown in Appendix B.

The method proposed in this study is then compared with the applied decision method, the LCC and the TGR values are calculated using the formulas proposed for both the alternatives (refer Appendix B) and then computed into the model.

4.4 Case Study – Result and Discussion

The facility management choose 'Alternative B' based on the LCC cost advantage over the 'Alternative A'. Even though, the capital cost of the LED lighting option is over 200 million South Korean Won (KRW), the application of the product accounts to over 50 million KRW in energy savings per year, enabling the company to reach break-even point of the investment in 3.59 years. Although carbon emission value is calculated, the decision is made solely based on the life cycle cost of the product. The carbon emission value calculated is used to acquire sustainable certification.

The result of the proposed method (as shown in Fig. 4.3) provides a visual

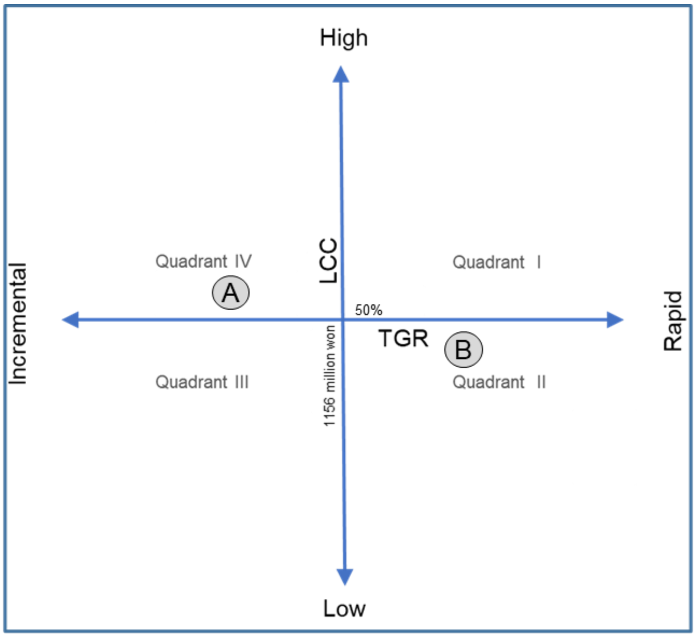


Figure 4.3 Case study decision model

comparison between the two alternatives in terms of LCC and TGR. LCC is calculated based on an assumed forecast of the product to be used in the facility. The relative gap between the LCC of each alternatives are significantly small in comparison with the gap between their TGR. The model recommendations is such as the 'Alternate B' should be chosen with caution, in partial combination and increased inspection frequency. Whereas the 'Alternative A' is a highly stable relatively and close to base LCC value, making it as the recommended choice and green certification efforts can be directed to other parts of renovation work.

The comparison of the proposed framework with existing methods shows similarities such as LCC being used as a decision making tool for product selection even in large-scale firms. However, LCC considered by the facility management is only until the return of investment achieved, that appeared to show the LED lighting option has significant cost advantage, which in reality considering as a long-term investment, the differences is small. The professionals look into the reputation of the brand, whereas the current study look into the reputation of the product in terms of performance criteria. In this case, although the company providing LED solution is reputed, the product selected here has a relatively new feature from the company, making it more susceptible to risk and obsolescence. Apart from visual advantage over existing method, the model developed provides important insights on the relations between the alternatives, would be supportive to the decision makers make rational decisions.

To enable sellers to place their products in the ideal quadrant relative to their competitors, it is important to provide products that are matured and lasts for a long period with respect to their technology and product quality. Moreover, sustainability factor of the products must also reflect their economic value. For example an environmental friendly product that compromises cost efficiency over its competitors cannot be a sustainable product, as the triple bottom rule for sustainability is social, economic and environment value.

4.5 Summary

The applicability study of the framework's application provided a clear picture of how the framework works in real scenario. The study also identified issues such as progressively developing historical data record of products in construction industry and lack of linearity of product lineup causing subjective judgements on successor and predecessor of certain products. Additionally, considering assumptions from local standards, helps providing more accurate decision solution.

Chapter 5. Conclusion

5.1 Research Summary

Reliability of data and the lack of knowledge are the two of the most important barriers preventing the spread of sustainable products in construction industry. Existing decision methods depends on these data and demands knowledge about the products and the decision methods to make decisions. Decision method for a comprehensive product category was observed to be a necessity, and so selecting nonstructural sustainable products as scope of the framework that is being developed was considered as a viable solution to resolve it. A simple decision making framework considering transparent factors is developed for nonstructural sustainable products, addressing the criteria- economic value, risks and obsolescence. The developed framework's application is examined through a sample project and issues and limitations were identified. Further, a case study on the frameworks application was performed and compared with the existing method used in the industry for better understanding of the application potential of the framework.

5.2 Contributions

The end-users of the framework would be professionals and decision makers specifically in SMEs. The applicability of the framework is expected to influence the spread of sustainable products globally in all scales of construction projects, prevented by the negative perceptions and difficulties in decision making.

The beneficiaries of the framework would be owners, construction professionals and public as the framework is anticipated to decrease the purchase of premature products released in the market, by enabling the decision makers to foresee to avoid purchase of such products.

The framework would be a step to encourage researchers to provide solutions that would be beneficial for achieving equity in construction industry in terms of research focuses, as research aimed to benefit everyone may not be more but not less important to contribute to advancement.

5.3 Limitations and Further Research

Limitations- The framework is specific to non-structural sustainable products and is not applicable to structural sustainable products.

Further Research- The framework approach could be used to provide decision for selection of structural sustainable products.

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www.ecolabelindex.com

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Appendix A – Factor Calculations for Sample Project

Life Cycle Cost Calculation:

Assumptions-

Maintenance cost: 2% of Capital Cost

Annual inflation rate: 2%

Residual Value: value of the number of years left in its useful life, which is understood as the time with complete warranty

Disposal Value: $4 / square foot

Specs\Company	Company 1	Company 2	Company 3	Company 4
Product Name	Slate	Single width Slate	Roof Slate	Solar roof
C_0	$27,440	$30,870	$38,141.6	$69,594
C_1	-	-	-	-$98,900*
C_2	$16,464	$18,522	$22,884	$41,756.4
C_3	-	-	--	-
C_4	$13,720	$13,720	$13,720	$13,720
C_5	-$10,976	-	-$15,256	-
LCC	$46,648	$63,112	$59,489.6	$26,170.4

Provided by the company*

Technology Growth Rate Calculation:

Date of introduction Vs Criteria with most significant advancement.

Specs\Company	Company 1	Company 2	Company 3	Company 4
Product Name	Slate	Single width Slate	Roof Slate	Solar roof
Product's Date of introduction	2013	1997	1988	2017
Criteria	Recycled materials used	Fire Rating	Recycled materials used	Solar power generation
Current functionality value of Criteria	25%	Class A	100%	undisclosed
TGR	0%	0%	0%	100%

Appendix B – Factor Calculations for Case Study

Documented factor calculation data:

1 지하 주차장에 설치되어 있는 삼파장 램프 및 형광등을 LED램프로 교제

[표2] 주차장 주요 전등 교체 후 비교현황

<table>
<tr><td rowspan="3">구분</td><td colspan="3">설치조명 (교체 후 조명)</td><td rowspan="3">교체 후 소비전력 [kW]</td><td rowspan="3">절감전력 [kW]</td></tr>
<tr><td>FPL 55W x 3</td><td>FL 32W x 1</td><td>FL 32W x 2</td></tr>
<tr><td>LED 40W</td><td colspan="2">LED 20W</td></tr>
<tr><td>지하 1 층</td><td>60</td><td colspan="2">0</td><td>2.300</td><td>3.227</td></tr>
<tr><td>지하 2 층</td><td>142</td><td colspan="2">69</td><td>7.060</td><td>11.160</td></tr>
<tr><td>지하 3 층</td><td>226</td><td colspan="2">182</td><td>12.680</td><td>18.740</td></tr>
<tr><td>지하 4 층</td><td>235</td><td colspan="2">182</td><td>13.040</td><td>18.764</td></tr>
<tr><td>지하 5 층</td><td>203</td><td colspan="2">179</td><td>11.700</td><td>17.590</td></tr>
<tr><td>지하 6 층</td><td>186</td><td colspan="2">161</td><td>10.660</td><td>16.180</td></tr>
<tr><td>지하 7 층</td><td>85</td><td colspan="2">69</td><td>4.780</td><td>7.335</td></tr>
<tr><td>지하 8 층</td><td>82</td><td colspan="2">54</td><td>4.360</td><td>5.169</td></tr>
<tr><td>합계</td><td>1,219</td><td colspan="2">896</td><td>66.68</td><td>98.17</td></tr>
</table>

기대효과

1. 계산조건: 지하 2 층,지하 3 층
   — 일일 조명 가동시간 = 16.5 시간/일(05:30~22:00)
   — 격등 점등시간 = 7.5 시간/일(22:00~05:30)
   — 연간 가동시간 = 7,391[h/년]
   *산출식 : {16.5[시간/일] x 365[일]}+{7.5[시간/일] x 365[일]/2[격등]}
   — 적용 소비전력 : 49.64[kWh]
   — 절감 소비전력 : 19.74[kWh]
2. 지하 1 층, 지하 4 층~지하 8 층
   — 일일 조영 가동시간 = 14.5 시간/일(05:30~22:00)
   — 격둥 점등시간 = 9.5 시간/일(22:00~05:30)
   — 연간 가동시간 = 7,026[h/년]

*산출식 : {14.5[시간/일] x 365[일]}+{9.5[시간/일] x 365[일]/2[격등]}

— 적용 소비전력 : 115.21[kWh]

— 절감 소비전력 : 46.94[kWh]

연간 전력절감 기대량

1. 지하 2 층, 지하 3 층

   LED 교체로 인한 전력절감 = 19.74 [kWh] x 7391 [h/년]

   = 145.898 [kWh/년]

2. 지하 1 층, 지하 4 층~지하 8 층

   LED 교체로 인한 전력절감 = 46.94 [kWh] x 7026 [h/년]

   = 329.800 [kWh/년]

   (가) + (나) = 145.898 [kWh/년] + 329.800 [kWh/년] = 475.698 [kWh/년]

3. 연간 전력절감 금액 = 연간 절감량 x 전기요금단가 (2016 년 평균단가 기준)

   = 475.698 [kWh/년] x 121.7 [원/kWh]

   = 57.89 [백만원/년]

4. 예상 투자비 : 207.9 [백만원]

   LED 등기구, SMPS, 기타 신설비용 포함

5. 투자대비 회수기간 = 예상투자비/ 연간 전력절감 금액

   = 207.9 [백만원]/ 57.89 [백만원/년]

   = 3.59[년]

6. 총 전력 사용량대비 절감율 (2016 년 기준)

   = (총 전력 절감량 / 총 전력 사용량) x 100

   = (475.698 [kWh/년]/ 32,807,951 [kWh/년]) x 100

   = 1.45 [%]

7. 이산화탄소 저감량 = 475.698 [mWh/년] x 0.4653 [tCO2/mWh]

   = 221.342 [tCO2eq]

   *전력 이산화탄소 배출계수 : 0.4653 [tCO2/mWh]

   건물 기준연도(2009년~2011년 3울 평균) 배출량 : 20,697[tCO2eq]

   건물 2017년 온실가스 예상 배출량

   : 20,661[tCO2eq] x 1.8[%] = 20,289[tCO2eq]

건물 2017년 온실가스 감축량= 20,697[tCO2eq] - 20,289[tCO2eq]

= 408[tCO2eq]

8. 전력량 절감에 따른 온실가스 배출 저감비율 (건물 2017 년 감축량의 기준)

= (221.342[tCO2eq] - 408[tCO2eq]) x 100

= 54.25 [%]

9. 건물 주차장 LED 전등 교체로 다음과 같이 절감 할 수 있음.

— 연간 전력절감 기대량 : 475,698 [kWh/년]

— 연간 전력절감 예상금액 : 57.89 [백만원/년]

— 투자대비 회수기간 = 3.59[년]

— 총 전력 사용량대비 절감율 (2016 년 기준) = 1.45 [%]

— 전력량 절감에 따른 온실가스 배출 저감비율 (건물 2017 년 감축량의 기준) = 54.25 [%]

Proposed framework's factor calculation data:

Life Cycle Cost Calculation:

Assumptions-

Required Lifecycle: minimum 5 years

Average florescent light life = 10,000 hrs, Average LED light life = 25,000 hrs.

Annual inflation rate: 1.8%

Residual Value: value of the number of hours left in its useful life, which is understood as the time with complete warranty.

Specs\Alternatives	Alternative A	Alternative B
Product Name	fluorescent lighting	LED lighting
C_0	43,884,000 KRW	207,900,000 KRW
C_1	1,005,274,542.58 KRW	715,811,834.95 KRW
C_2	-	-
C_3	131,652,000 KRW	207,900,000 KRW
C_4	-	-
C_5	-	-
LCC	1,180,810,542.58 KRW	1,131,611,834.95 KRW

Technology Growth Rate Calculation:

Date of introduction Vs performance criteria with most significant advancement.

Specs\Alternatives	Alternative A	Alternative B
Product Name	fluorescent lighting	LED lighting
Product's Date of introduction	2007	2017
Criteria	Luminous flux	New smart dimming energy saving
Current functionality value of Criteria	3,600 lm	-
TGR	0	100%