

Application of Formal Concept Analysis in Estimating the Cost of Green Buildings

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Sustainable development and green building concepts are based on increasing the efficiency of resources used in a structure while decreasing the negative impact on people and the planet. In order to achieve long-term economic gains and simultaneously satisfy environmental and social constraints, “green” features must be analyzed from a life cycle perspective, e.g., Life Cycle Cost (LCC). However, during the early project design phase, when it is critical to determine desired “green” features, providing an accurate cost estimate is always a challenge. Assembly cost estimation is a common method for developing accurate cost estimates in the early design phase, due to its flexibility to accommodate design changes and capability to provide detailed estimates based on reasonable scope assumptions. Thus, this study is intended to explore the integration of building assemblies and the performance factors of “green” features, so that the process of deriving “green”-related cost can be facilitated by using computer tools. The aim of this research is to propose a model to allow users to determine the cost of various alternatives for achieving certain “green” features. Within the context of this paper, concurrent analysis of assembly cost estimates and “green” properties will be achieved through the adoption of formal concept analysis.

Key words: Sustainability, Green Building, Life Cycle Cost, Assembly Cost Estimation, Formal Concept Analysis

Introduction

Sustainable development introduced the need for specialization in green buildings. In the U.S., buildings currently account for 14% of potable water consumption, 30% of waste output, 38% of carbon dioxide emissions, 40% of raw material use, 39% of energy use, and 72% of electrical consumption (USGBC, 2010). With the high amount of resource usage and growing population, the green building concept is based on increasing the efficiency of resources used in a structure while decreasing the negative impact on people and the planet. In order to achieve long-term economic gains and simultaneously satisfy environmental and social constraints, “green” features must be analyzed from a life cycle perspective, e.g., Life Cycle Cost (LCC). Estimating the cost of a green building, however, is affected by various parameters which complicate the process. During the early project design phase, it is a challenge to integrate green features into the cost calculations while fulfilling the project design requirements. Traditionally, the design and estimation processes are performed separately, which creates cost blackout periods during the design process; it is thus ideal to have a software tool that automates the cost estimation process during design.

The automatic derivation of LCC based on design requirements is a great challenge. The study presented herein is intended to be a stepping stone toward achieving this goal. One of the key issues is the proper selection of cost items that match the design requirements. In order to produce reliable cost estimation, all design requirements should be clearly delineated in a computer-interpretable representation. Secondly, a performance-based cost database of building products and assemblies should be created to support assembly-based cost estimation in the early design phase, due to its flexibility to accommodate design changes and capability to provide detailed estimates based on reasonable scope assumptions. Finally, a proper method for the mapping of design requirements, building products, and assemblies should be decided upon to form the basis of the automatic cost estimation system. This paper will focus on the third aspect of the process.

In this research, the concurrent mapping of design requirements, building products, and assemblies are achieved by a concept analysis method. Concepts represent categories of things or objects in the world, such as design concepts, building products, or systems. This paper will investigate whether concept analysis techniques can be used to determine the association of a cost assembly, with relevant design requirements, so that the LCC estimation process can be treated as a product/assembly selection process. For this purpose, Formal Concept Analysis (FCA) is proposed as a more comprehensive method to perform LCC in this study. FCA will be adopted, assuming that the design requirements and green building performance indicators are pre-defined together with the assembly cost estimation data.

Identifying Green Building Performance Indicators

As sustainable designs continue to evolve in the U.S. and other countries, current methods for measuring the actual benefits of these designs have come into question. The qualitative and/or quantitative measures of sustainability have resulted in the creation of "green" performance indicators, which are created to show the impact and cost-effectiveness of the building. The performance of green buildings can be evaluated based on their effects on people and the environment. For example, the U.S. Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEED) program is a rating system used to assess the energy and environmental performance of buildings. LEED addresses building performance in five key areas of human and environmental health: sustainable sites, water efficiency, energy and atmosphere, materials and resources, and indoor environmental quality. The rating system for new construction uses a point-based system to award four levels of certification; Certified (40-49 points), Silver (50-59 points), Gold (60-79 points), and Platinum (80+ points) out of 110 points, including 6 points in Innovation in Design and 4 points in Regional Priority categories (USGBC, 2010). LEED prerequisites and credits are achieved by implementing certain strategies, techniques, and technologies in the design and construction of buildings.

In the scope of this study, LEED performance factors involving the materials and resources category are applied to evaluate an example situation. This category addresses three main issues, conservation of materials, using environmentally preferable materials, and waste management and reduction, as buildings generate 30% of the waste and use 40% of raw material in the U.S. (USGBC, 2010). The idea is to "reduce, reuse, and recycle" materials used in building construction. In this way, LEED has the goal to promote the usage of more environmentally-friendly materials to decrease waste, and reuse and recycle materials that are already extracted, manufactured, and even used at the site. It is important to note that LEED performance indicators for this category should be identified and applied by considering the properties of the specific project. In this case, a small assembly, such as a room, is considered from the perspective of waste reduction and the related materials selection credits. Credits in the materials and resources category, as well as the only prerequisite, are shown in Table 1 with their respective LEED credit numbers.

Table 1

"Green" performance indicators for the example assembly

Credit No (MR)	**Credit Title**
Pre-Requisite 1	Storage & Collection of Recyclables
Credit 1.1	Building Reuse - Maintain Existing Walls, Floors, and Roof
Credit 1.2	Building Reuse - Maintain Existing Interior Nonstructural Elements
Credit 2	Construction Waste Management
Credit 3	Materials Reuse
Credit 4	Recycled Content
Credit 5	Regional Materials
Credit 6	Rapidly Renewable Materials
Credit 7	Certified Wood

The term "assembly" here refers to a set of items which includes all materials, equipment, and labor that are used in construction. In this case, the components of the room assembly are simply materials, as "green" indicators have been limited to material selection credits only. The material elements of the room can therefore be defined as concrete, metal, woods, glass, carpet, and acoustical ceiling tiles. When the recyclability of these materials is investigated, the following outcomes are obtained:

Concrete waste may be ground up and used for pavement construction or as a fill material;

Metals are readily recyclable as most steel has been recycled at least once;
Wood waste can be ground up for particleboard, mulch, or to mix with sewage to make fertilizer;
Unbroken glass containers can be readily recycled;
Used carpet can be recycled into plastic pellets to make numerous products such as wheel stops; and
Ceiling tile materials and grid systems can be recycled.

Among the outcomes, the materials are either assumed being recycled or used in construction waste management. From the recyclability point of view, it can be observed that, with the exception of concrete and wood, the materials satisfy Credit 4: Recycled Content, as they are all recycled in some manner. On the other hand, concrete and wood are included in Credit 3: Materials Reuse by using salvaged, refurbished, or reused materials from another assembly or related job. This waste management plan allows the least possible amount of waste to be generated. In addition, the approach aims to reuse, salvage, or recycle as many of the waste materials as economically feasible.

The most important step is to identify the relevant “green” performance indicators and determine their ratings based on the linguistic information provided. The matching of the “green” features and material information can result in credit numbers that sum-up to give the level of “green” situation for the assembly. The level of “green” situation can suggest one of the certification levels as certified, silver, gold, or platinum, as well as the required life cycle costs for this certification level. In addition, if a certain certification level is intended, the required material properties and level of “green” indicators can be observed by a connection set between these variables. In this paper, a simpler version of this connection will be performed by using FCA to calculate the LCC of a certain certification level.

Defining Life Cycle Cost (LCC)

Life Cycle Cost (LCC) is defined as the total of costs within the life cycle of a structure (Blanchard & Fabrycky, 1998). Hunkeler et al. (2003) also describe LCC in the same manner, while another definition in Fuller & Petersen (1995) explains LCC to include all costs from owning, operating, maintaining, and finally disposing of a project. Additionally, Fuller & Petersen state that LCC can be used to choose various design options based on performance indicators. In this case, the performance indicators are “green” features that will allow for comparison between ranges of design alternatives.

The procedure for estimating LCC has a few basic steps, as summarized by Fabryck (1991). First, the problem related to LCC is identified. Then, technical requirements and alternative solutions are investigated for this problem. The process continues with the development of cost details by year and selection of a suitable cost model. This allows for the estimation of cost and the creation of cost profiles for each year. Based on this information, several charts are prepared for alternatives and costly items. Afterwards, test alternatives are identified with consideration to risks involved, and the process ends with the selection of the preferred course of action by using LCC.

In order to apply FCA, the problem related to LCC (first step in the LCC procedure) should be identified based on both the “green” features and design requirements. The cost data for alternative solutions will form a base for cost estimation. Assembly cost estimation is a common method for developing accurate cost estimates in the early design phase, due to its flexibility to accommodate design changes and capability to provide detailed estimates based on reasonable scope assumptions. The method allows changing the level of “green” indicators as well as the type of building assemblies to observe the variation in cost. This feature is very valuable to users as it permits the presetting of a cost limit for the project in the design phase, where most of the green building features are determined. In other words, by using the assembly cost estimation method, the essential “green” features of the project can be defined to both satisfy design requirements and estimate an affordable LCC in this early stage. After conceptual estimating is performed, the integration of design requirements and “green” indicators can be achieved by FCA. The construction of the FCA model for the room assembly will be discussed in further detail below.

Estimating the Cost of “Green” Features by Formal Concept Analysis (FCA)

Formal Concept Analysis (FCA) is a technique for data analysis and knowledge representation that was first developed by Wille (1982). He defined FCA as a method “based on the philosophical understanding of a concept as a unit of thought consisting of two parts: the extension and intension (comprehension); the extension covers all objects (entities) belonging to the concept while the intension comprises all attributes (or properties) valid for all those objects." There is a variety of FCA uses in literature. As examples, Carpineto and Romano (2004) presented an overview of FCA applications in information retrieval, while Tadrat et al. (2012) used FCA to propose a vector model for cased-based reasoning. No matter what FCA is used for, a formal concept pair is made up of "an extent," the set of formal objects, and "an intent," the set of formal attributes, for the concept. A good way of defining the elements of a formal concept pair is to choose object-like items as formal objects and their features or characteristics as formal attributes (Priss, 2005). Based on this information, material properties in the example room are considered as objects while "green" features are regarded as attributes. The relationship between material (object) and "green" features (attributes) is set so that any material can contain any "green" features as its embedded property.

A formal concept pair and the relation between objects and attributes form a "formal context." Formal context is presented as cross tables showing objects at the left side and attributes at the top of the table. The relationship between them is shown by putting crosses at the intersection of the relevant objects and attributes. A formal context for the example room is presented in Table 2. While forming the formal context, it is decided whether each material has or does not have the given "green" credits. Building Reuse and Materials Reuse credits are assigned to the materials that can be recycled so that they can be obtained from a previous project. Additionally, these materials fulfill the Storage & Collection of Recyclables prerequisite and Recycled Content credit, as they can be stored to be recycled and have a certain percentage of postconsumer and pre-consumer recycled contents. As the wastes of concrete and woods are explained to be used for other assemblies in the previous section, Construction Waste Management is an applicable credit for both. The remaining three credits are decided by judgment so that Regional Materials is marked for concrete and woods, since woods are accepted to be rapidly renewable and certified. In this way, all relationships among the objects and attributes are specified.

Table 2

Example formal context

Green Features / Materials	Storage & Collection of Recyclables	Building Reuse (1.1 & 1.2)	Construction Waste Management	Materials Reuse	Recycled Content	Regional Materials	Rapidly Renewable Materials	Certified Wood
Concrete			X			X		
Metal	X	X		X	X			
Woods			X			X	X	X
Glass	X	X		X	X			
Carpet	X	X		X	X			
Acoustical ceiling tiles	X	X		X	X			

When the set of all attributes that has a connection with the same single object (or vice versa) is identified, it will not be possible to add further objects or attributes to this set. This is simply because no other objects or attributes would be able to create more relationships in common. In other words, the relationship between two sets, objects and attributes, will be closed. A pair of objects and attributes formed in this manner is called a "formal concept." An example formal concept is formed by starting from wood materials and deriving all "green" properties thereof. This set is a formal concept, as it can neither be enlarged nor reduced.

Similarly, starting from Construction Waste Management, its objects, such as concrete and wood materials, are obtained. In addition, all the common attributes of two or more objects can be identified from the formal context. For instance, the common attributes of concrete and wood materials are Construction Waste Management and Regional Materials.

When sets of several formal concepts are identified, they can be visualized in a "concept lattice." Concept lattice is a type of line diagram where nodes show formal concepts and lines represent relationships. The top and bottom nodes can be universal and null in order to encompass relations with all extensions and intentions of the formal concept. The top node becomes universal when none of the attributes have relationships with all objects. In a similar manner, the bottom node becomes null when all of the attributes have relationships with at least one of the objects. The concept lattice for the example room is shown in Figure 1.

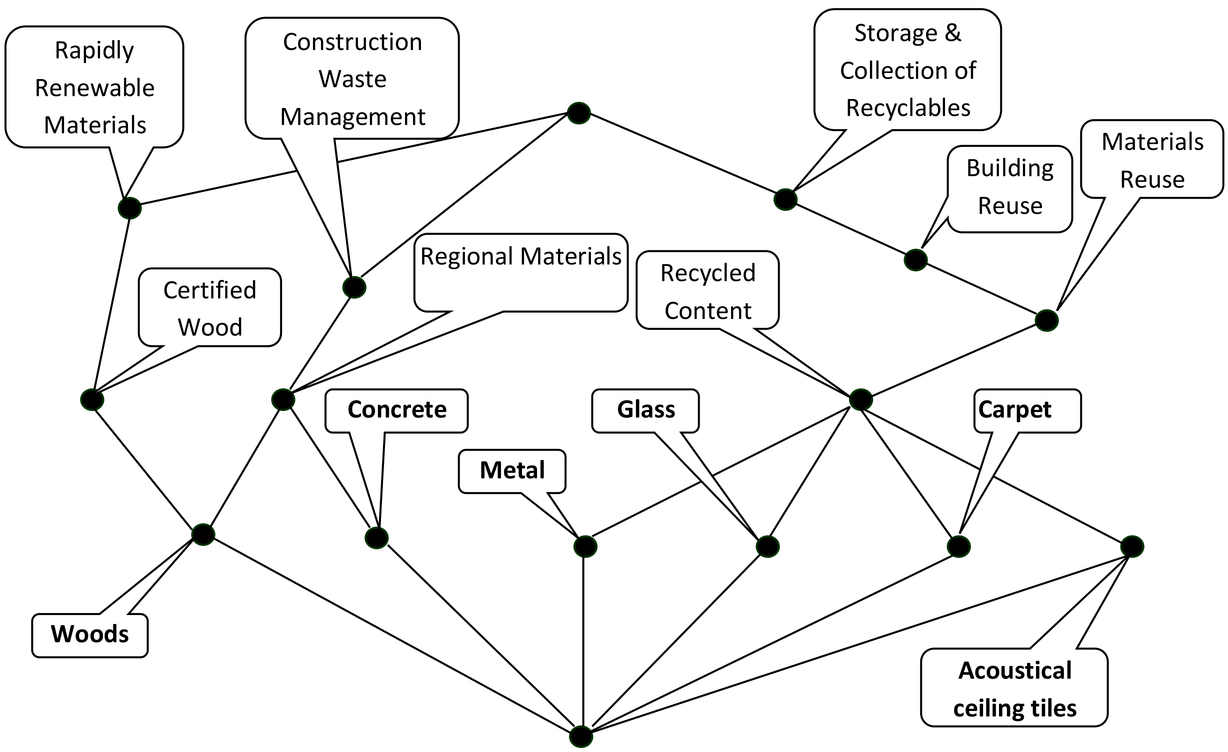

Figure 1: Example concept lattice.

Various paths in the concept lattice can be resolved by starting with an attribute and continuing on the path until it ends on an object node. As an example, starting from the universal node, the path goes to the Construction Waste Management node and continues through the Regional Materials node, until it connects to the Concrete object node. Finally, this node will end on the null node. This path identifies a formal concept pair composed of Concrete as object and Construction Waste Management and Regional Materials as attributes.

Until now, the formal context and concept lattice regarding the example room are constructed. The paths allow the matching process between design requirements embedded in materials and cost data built in "green" features. Once the design requirements and "green" indicators are defined in a computer-based environment and this concept lattice is run, the paths will be developed automatically. By successfully inputting the information into to the model, the user will be able to derive a cost output based on the required design and "green" credit levels of the structure.

As an example, the proposed concept lattice will be used to analyze two alternative "green" levels and perform assembly cost estimation with FCA. First, two alternative "green" levels are created based on LEED materials and resources credits. For this purpose, all credits in materials and resources category should be handled one by one. As an example, Storage & Collection of Recyclables should be included in both alternatives for being a prerequisite. It is not possible to use Building Reuse (1.1 & 1.2), as only a certain portion of the structure is being analyzed. Both alternatives involve Construction Waste Management Plan.

First alternative:
contains more than 20% locally sourced and manufactured materials (2 points)
diverts more than 75% of all construction waste from wood, drywall, etc. from landfills (2 points)
selects more than 2.5% of the total value of all building materials to be rapidly renewable (1 point)

uses more than 50% wood-based materials as approved by the Forest Stewardship Council (FSC) (1 point)

Second alternative:
contains more than 20% locally sourced and manufactured materials (2 points)
diverts more than 75% of all construction waste from wood, drywall, etc. from landfills (2 points)
uses more than 10% of the total value of all building materials as salvaged or refurbished (2 points)
uses materials with a total recycled content exceeding 10% (1 point)

For the first alternative, starting from the universal node, the first path goes through Construction Waste Management and Regional Materials node to connect to Woods. The second path goes through Materials Reuse and Recycled Content and end up at the Metal object. For the second alternative, the path goes to the Construction Waste Management node and continues through the Regional Materials node, until it connects to the Concrete and Woods. Additionally, second path goes through Rapidly Renewable Materials and Certified Wood, until it connects Woods.

Considering the concept lattice paths for both alternatives and different material options that can satisfy design requirements, two room alternatives are obtained for cost estimation. The details of the materials for both alternatives are shown in Table 3. Two room alternatives include three assemblies as exterior and interior walls and floorings. Material types are selected based on the concept lattice objects. For example, the path is connected to Woods object for the first alternative. Thus, materials are selected as variations of wood products. Materials for the second alternative are selected in a similar manner.

Table 3

Room Alt 1 and Room Alt 2

	Room Alt 1	**Room Alt 2**
Activities	**Material Type**	**Material Type**
Exterior Walls	Wood, OSB on both faces	Concrete block wall
Interior Walls	Drywall partitions with wood stud framing	Drywall partitions with metal stud framing
Flooring	Wood, bamboo	Wood, prefinished white oak

After room alternatives are created, the information is transferred to MS Excel for cost estimation. Unit cost for each material type (per floor area of building) is used for estimation. The results are shown in Table 4. At this stage, FCA analysis method has enabled us to determine the cost of alternatives for achieving certain "green" levels. If the analysis is taken to the next level, then two alternatives can be compared based on eco-efficiency. Eco-efficiency aims for simultaneously reducing environmental impacts through "green" credits, and delivering feasibly priced items. When Room Alt 1 and Room Alt 2 are compared in terms of "green" credits, the first alternative has 6 credits while the second one has 7 credits. Thus, they have similar "green" levels that can fulfill design requirements. In order to decide on which room assembly will be more eco-efficient, cost estimation results should also be considered. Although the costs for interior wall assemblies (drywall partitions with wood or metal stud framing) have similar costs, the costs for exterior walls and flooring have considerable differences between two alternatives. Concrete block wall costs nearly 2.5 times OSB exterior walls, while prefinished white oak floor costs nearly two times bamboo flooring. In total, the cost for Room Alt 2 is considerably larger than the cost for Room Alt 1. As their "green" criteria are similar, it is more eco-efficient to select Room Alt 1 and use mostly wood-based materials in the construction of this example.

Table 4

Room Alt 1 and Room Alt 2 Cost Estimation Results

Room Alt 1		**Room Alt 2**	
Material Type	**Cost**	**Material Type**	**Cost**
Wood, OSB on both faces	$5,191.90	Concrete block wall	$13,079.99

Drywall partitions with wood stud framing	$5,594.11	Drywall partitions with metal stud framing	$5,501.64
Wood, bamboo	$5,668.32	Wood, prefinished white oak	$9,123.30

The concept lattice structure given in Figure 1 includes the four different "green" certification levels of attributes and their appropriate types of materials in objects. This concept lattice can be extended to show the "green" certification levels and types of materials as separate nodes. This will result in an increase in path number and complexity in the path structure. The aim of this study is to allow a user to find a path starting from a required "green" level and passing through its related material types. In this way, design requirements will be selected based on the "green" level of the assembly, or vice versa, if the material type is preset and the "green" features of the material can be detected by following its path. As the attributes/"green" indicators in a formal concept pair are defined to include cost data, the cost estimation of any object/material can be obtained by using its path in the concept lattice.

Although the example concept lattice in this paper is a simple structure, the concept lattice of a whole building will be very complex because of the high number of nodes and relations needed to represent the building. Additionally, it will not be limited to Materials and Resources credits only. The objects will also comprise installation items, such as labor cost, while the attributes will contain properties from all five (and maybe more) "green" levels. As the number of objects and attributes increases and sub-objects and sub-attributes appear, the analysis of the path becomes too complex to obtain cost estimation by hand; the ideal way to construct and analyze concept lattice, therefore, is with the aid of software. For this purpose, the building assemblies and performance factors of "green" features should be defined and represented in a computer-based environment, and assembly cost estimation should be performed based on this information. After completing these steps, the "green"-related cost can be derived by an automatic path selection process.

Conclusions

The aim of this research was to present the construction steps of an automated FCA-based model for the integration of assemblies with "green" features, in order to obtain a reasonable LCC estimate in the early design phase. The concept lattice constructed in this study presented the relationships between building assemblies and "green" credits in a path structure by treating assemblies as objects and "green" features as assemblies. The concept lattice defined cost by connecting a "green" feature to its required material types via a pathway process. In this way, the relationships between cost data, which were based on "green" performance indicators, and design requirements, which were set by the project team, were used to estimate conceptual cost. An actual assembly cost estimation example was generated. Two room assemblies were compared based on "green" levels and assembly costs. The results show that it is possible to represent building assemblies with FCA and decide on their eco-efficiency.

Although a simplified model was presented in this paper, as a concept lattice, it can be further enlarged by inserting other types of objects and attributes. With an enlarged number of objects and attributes, the model becomes too complex to be analyzed by hand. Therefore, an automatic path selection process based on the concept lattice structure is proposed in this paper. As such, regardless of how the concept lattice is enlarged, if the building assemblies and "green" features are properly represented in a computer-based environment, the model will output an acceptable cost estimation. This will prevent users from having to redo all calculations when there is a change in the design or "green" credits. Additionally, the concept lattice model for LEED MR Category can be extended to include other LEED categories and handle the building assemblies in an entire project.

The importance of the representation of building assemblies and "green" features is obvious in an automatic cost derivation model, as it would not be possible to obtain a reasonable cost estimate without proper inputs. Therefore, future studies should be performed based on knowledge representation techniques to convert the linguistic design and "green" credit data into formal representations. The knowledge of building assemblies and "green" features can then be used as inputs in the concept lattice previously constructed with the software. As the cost data is integrated in "green" performance indicators, the cost estimate of the project can be derived through the automatically selected paths, which will minimize man-made errors and contribute a systematic "green"-related cost estimation tool to the industry.

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