Adaptive Architectural Value Engineering

Methods

CD.Meyer
North Dakota State University
Department of Architecture and Landscape Architecture
Fall 2017

Research

Optimal Frontier

To develop an architectural design with an optimal solution, an understanding of the mechanics of design process becomes important. In *'Design by Optimization in Architecture, Building, and Construction'*, architectural design is defined as *a goal-directed activity in which decisions are made about the physical for of the building and their components in order to ensure their fitness for the intended purposes. Further, that design itself is comprised of three primary identifiable phases, problem analysis, design synthesis, and design evolution, which are performed in a cyclical process by conscious or unconscious sorting of design goals.* (Greo, Radford, 1988)

This process of design moves from generalizations about design defined in a broad terms, methods, and doctrines, and results in optimal design solutions. These solutions may or may not be the optimal answer to the design problems. The cyclical form of design becomes well suited for the introduction of value mapping and continual improvement practices. Architectural design is not often thought of in this manner, lacking proper evaluation of design changes and post occupancy analysis. Gero and Radford, 1988, refer to the a bias present in design practice in which a designer over rely on personal judgment in the decisions affecting the tradeoffs between design solutions without proper numerical or practical reasoning to meet client or social expectations at the cost of performance in the final product.

Does form follow function, or function follow form? In a optimal method of design, the cyclical evolution of the solutions allows for both statements to be true. This allows a balancing of aesthetics to performance sought in an optimal solution to a design problem.

"Each building has its own grammar, its distinct vocabulary of pattern and form. All parts of the building from the smallest detail to the overall form thus speak the same language. The grammar may be completely different for two buildings..."
(Wright, 1952)

Constraints

The constraints imposed by site conditions, regulations, and client directives, limit the range of possible design variations. "*Architects and other designers tend to work within a language (a style) of design that is peculiar to a individual, a school, or a age."* (Gero and Radford, 1988) Greo and Radford (1988) and Wright (1952) define design or design synthesis as limited to, and practiced with a language and style which may not be related to other forms

Gero and Radford (1988) refer to the limitations of design evolution, "*design solutions in any particular situation are not unlimited and cannot be treated as if they were."* This statement defines the limiting factor, with the applicability of one case presenting an optimal solution which is foreign or inappropriate in another. Each design will present its own defined optimal solution which may or may not be generally applicable to design thinking

Methods which may prove applicable to general design thinking must be adaptable, translatable, to different forms of design language or grammar. By seeking commonalties in design and applying and evaluating different design methods, a synthesizing of a optimal solution may occur.

Design Synthesis

Design synthesis is the making of decisions within a design language and under project specific constraints, using models based on information about whether the decision that will further the advancement of the body of design goals. (Gero and Radford, 1988) Design has a need, in the seeking of optimal solutions, to correlate concerns and constraints in the appraisal of a design solutions. The appraisal of design solutions is completed in two manners, non-preference, and preference methods.

"Before a design can begin a designer needs a model of the problem, in the mind, written down on paper, expressed as diagrams, expressed as symbols, or some combination of theses." (Gero and Radford 1988) In the development of an optimal method numerical symbolic models present the form for optimization, describing a design or project in dynamic terms. This form of modeling has three distinct categories: simulation, generation, and optimization. (Greo and Radford, 1988)

Simulation

Model simulation predicts the performance consequences by manipulating a numerical model. All evaluation and decisions are external to the model.(Gero and Radford, 1988) This form will develop a field of options based on none adaptive function. In simulation modeling the model parameters do not change internally and are none adaptive. Simulation has little value in optimization, except in the testing and defining of benchmarks for evaluation to be used in a manipulative generation models.

Generative Modeling

Generative modeling explores the consequences of a set of decision rules, with some form internal evaluation and changing of model parameters. (Gero and Radford, 1988) This form of modeling when combined with simulated outcomes will produce a optimal method for the evaluation of project specific parameters.

"Optimization is defined as the ranking of performance solutions or partial solutions when measured against the defined objective or optimal outcome." "Optimization models effectively searching the whole field of feasible solutions and identifies those suited to the designers stated goals. This is an attempt to answer the designer's fundamental question of what is the best solution."(Gero and Radford, 1988)

Methods of Selection

Non Preference Method

Non-preference methods of evaluate a field of possible solutions and selects an optimal point, with no evaluation or reference to designer preferences.(Gero and Radford, 1988) This method will return an optimal solution, but at the cost of other criteria. This allows for easy evaluation of purely numerical forms of optimization but does not take into account aesthetic qualities of a design which are important evaluation references in critical architectural design. The use of preferential methods of evaluation are needed to properly evaluate the all the design criteria presented by the nature of architectural design.

Perference Method

Preference methods of design evaluation take into account some prior assumptions of relative importance (in the design) and use this information in the generation of a field of solutions. (Gero and Radford, 1988)

Limitation to Optimality

A main limitation to generation of a optimal solution is the correct defining and correlation of variables and objectives. The correct definition of variables is important, and needed in the formation of a prescriptive informative model.

Value Defined

Value is a self defined ranking of either, or both, quantitative or qualitative variables. Value is the perceived or actual value of an object, method, or process. The self defining and ever changing nature of value is its most limiting factor to the useful introduction in design processes. This self defining nature of value, limits its use in over general application to design problems. Value is the optimal return of the sum of all internal and external variables and constraints. It becomes important to isolate value from quality in all methods of design optimization.

Quality Defined

Quality can be defined as the state of performance or durability of a process, method, or material. Quality in the built environment relates to product finish, methods of construction, and effectiveness of the environmental success of a built environment.

Economic Variables

Economic factors are the quantitative results of market function. Market functions are exogenous variables outside the control of a designer. These variables are further defined as the broad social and financial trends of a context in which a designer practices.

Value Variables

Value variables are either or both, qualitative or quantitative user defined and ranked factors of importance. These variables in architectural design are commonly attributed in terms of quality of material, perceived value of an object, or the cost to return ratio of a project.

Endogenous Variables

Endogenous Variables, are model variables are ones that a designer is in control of. These relate to some forms of budgetary limits and material selection.

Exogenous Variables

Exogenous variables, are model variables which are outside of the control of a designer. These variables can be accounted for in modeling, and relate to economic trends and supply prices.

Discrete Variables

Discrete variables are finite in their discretion and limited to a specific number of answers or values.

Discontinuous Variables

Discontinuous variables range in value based on threshold of imposed by each specific case.

Methods of Optimization

Optimization uses selected variables in the selection and evaluation of optimal solutions to design problems. These selected variables take two forms, user controlled endogenous and externally fixed exogenous variables. Each variable type may or may not be dependent on a model as whole, or a singular optimal point. These variables should be accounted for, and defined for proper evaluation of optimal solutions. Exogenous and exogenous variables are used to define test model parameters.

Optimization can be defined as the optimal value received by and optimal solution. This solution can be either numerical or a qualified benchmark of performance that is either an internally controlled user defined or externally defined objective, which must be accounted for in model parameters.

Architectural Variables

Variables relating to architectural design practice are usually defined as a specific value related to material, size, or as a limit or threshold imposed by building code regulation. These two forms of design variables are defined as either discrete or discontinuous. (Gero and Radford 1988) These variables play little role in optimization processes since they are usually external exogenous and fixed.

Benefit is received from these variables is in allowing the definition of constraints and bounds the field of possible singular solutions. This would result in the improvement of overall model efficiency.

The identification of requirements, and an understanding of constraints allow for the accurate evaluation of new and existing technologies in economic terms and code compliance. The evaluation of economic factors, incentives and funding, code enforcement, standards of construction, climate, geology, and vernacular appropriateness of style , in the development of a field of optimal solutions to architectural design problems.

Optimization Simply Defined

Optimization can now be redefined into simple, commonly understood terms, as the maximization and or minimization of a defined problem or wanted condition, to return a optimal solution. To create an optimal solution to a design or in construction, several methods can be employed. Each method will vary to meet defined outcomes. Historically, optimal solutions to architectural problems was reached and understood as result of a simplification of form, construction methods, and materials.

> *"It is not only necessary to get rid of all unnecessary complications in construction, necessary to use work in the mill to good advantage, necessary to eliminate so as far possible, field labor which is always expensive: it is necessary to consolidate and simplify the three appurtenance systems – heating, lighting and sanitation. At least this must be our economy if we are to achieve the sense of spaciousness and vista we desire in order to liberate the people living in the house.* (Wright, 1952)

The consolidation of design components is one method which allows for the simplification of the built environment. This is easily implemented and applied by the adaptation of and use of existing principles and methods. The resulting solutions can be used in simulation and generation of the design solutions.

Feasibility Considerations:

How does the built environment meet occupancy standards?

It is critical to evaluate materials, systems, and practices to understand the performance criteria presented by each. Performance is broadly defined and dependant on both technological advancement, and the context in which the technologies are applied. Social factor will affect the performance outcomes of the built environment. These social factors are exogenous and outside of designer control.

Having clear performance objectives will drastically affect the success of optimal design solutions. It is necessary to be practical in the selection of design performance criteria.

Contextual Reasoning

Historical and Current

Traditional methods of residential construction have been predominantly unchanged for the past 160 years, with mostly homes constructed as wood framed, stick, and site built houses.

More recent trends in housing economics have been greatly distorted by volatile economic and environmental factors. Growth rates in domestic residential construction reflect this, with flat levels of growth since 1983, when the growth rate was 7.83 percent. In 2017, the growth rate in construction was within a range of three percent. [1] Historically, previous to 1950, the rates of sector growth ranged annually from thirty to fifty percent.

In his book, *'The Rise and Fall of American Growth; The U.S. Standard of Living Since the Civil War*,' Robert Gordon states, *"many innovations that lead to both an increase of production and efficiency can only occur once."* Coupled with the views of economist, Herman Daly, that the economy is dependent on the Laws of Thermodynamics, one can frame the level of housing output and construction as a important factor in the economic health of domestic markets.

Current economic and growth trends show an economy in a declined rate of product and growth, which is incapable of higher rate of growth without drastic innovation with efficient capitalization of finite mineral and energy resources.

These trends point to an economy in a state of decline. These limiting factors significantly constrain any economic and social growth potential that could match prior historical production of industrial growth . A redefining of how our housing economics are viewed is needed.

Redefining of the Domestic Economy

Kenneth Boulding, in his book, 'The Economy of the Spaceship Earth,' wrote of two types of prevailing economies, the "spaceman, and cowboy economies."Boulding explains that, a *"Cowboy Economy*," is one that is gauged by a quantity of production and the level of consumption. This definition matches the historical industrial growth, and energy and material consumption seen in domestic markets before 1972.

The second economic classification, according to Boulding, is a *"Spaceman Economy,"* which is concerned with stock maintenance of existing resources and the optimization of processes and material use. This is achieved by the use of innovative technologies. This definition of economic function matches the dogmatic beliefs present in present methods of sustainable design and construction.

Housing as an Economic Tool

Domestic residential construction is dependent on the availability of affordable financing. Financing is available through private or government sector lenders, each having requirements which must be followed in design and construction. Both available funding and incentive are necessary to move conceptual design to active construction. Budgetary limits will define the scope of design and the limitations to performance. The success of new residential construction is based on the effectiveness of funding resources and incentives to build.

In 2016, 466.9 billion USD was spent on residential construction. This figure presents significant opportunity for improvements in residential construction methods.[1] New technologies, building products, and construction methodologies will greatly improve the standards of living. Investment in residential construction creates new jobs and impacts the health of local and regional economies. The Improvement of building methods and practices allows for the construction of homes with a better overall durability. The construction, maintenance, and operating costs that are part of home ownership contribute sustainably to the economic burden of the household. Better quality construction will decrease future maintenance costs and limit the need for repairs or replacement.

1. Bureau of Economic Analysis

Housing Life

The expected life span of domestic residential construction does not match that of its makeup of individual components. This statement is proved by the current average life span of housing as thirty five years, domestically. This is a result of exogenous economic variables. This economic condition correlates with terms of amortization, with periods ranging from fifteen to thirty years as an average.

The planned obsolescence of housing and stock maintenance is also limiting, though occurring at a lessened rate. The analysis and use of value engineering allows for the correlation and evaluation of these trends.

Ethical questions arise from the concept of using residential construction as solely an economic tool. Value engineering and optimal practices dictates that both the use and quality of materials and the performance must have a return on investment over the period of use or life expectancy of built environment. Domestic residential design and construction is found to rarely follow value methodologies.

A Need for New Methods

Professionals who are employed in the design and construction of new homes, need tools and methods that provide guidance in the selection of materials, technologies, and construction systems in a adequate and practical way. The integration of building professions in residential design and construction is necessary for the continual improvement of performance. The design process should include architects and engineers, building contractors, allied trades, product manufacturers, and critically the client.

It must be taken into account that due to the broadening scope of domestic residential design and construction, that knowledge bases, and methods will vary greatly based on jurisdiction and from professional to professional. New methods and practices need to be defined in clear and relevant terms for mass audiences.

The application of cost analysis and integrated design tools allow far more affective impact on design improvement. Algorithmic cost and design functions applied in methods of linear programming optimization allows the linking of improvement theories to practice.

Value Engineering

Value engineering is a systematically structural way of approaching design by developing an optimal solution to design projects, products, and processes. Value engineering is a commonly practiced method of critical design and analysis in construction and manufacturing. It provides both methods and philosophical doctrines for the evaluation and development of building performance to economic solutions. Value model analysis, analyses the performance variables of the designed environment to derive the lowest cost per opportunity optimal solution. This would be defined in common terms, "the best bang for your buck." In this type of modeling terms or factors can be defined as either quantified or qualified variables of both endogenous and exogenous nature and measure. This type of analysis is mechanically scientific and principally holistic. It has the possibility for further application in architectural design.

Cost Benefit Analysis

Professionals practicing in the design and construction fields should perform cost benefit analysis throughout the totality of a project. The complexity of evaluative studies, range from simple to complex. Analysis and evaluation should be crafted relative to each case, changing in measure and scope varied with the desired end use goals. The forms of accepted analysis in contraction are first cost, also known as simple cost, return on investment, and life cycle analysis, linear programming optimality analysis.

The recommendation for materials, technologies, and building techniques are most times selected by having the least first cost or upfront cost. This method does not account for the long term performance outcomes or the lifetime quality of the product or methods.

The early identification of budget goals and constraints allow for the shifting of budgetary allocations to increase the performance of the final product. Different interpretations of the projects emphasized goals have the tendency to shift performance and economic criteria. . A developed understanding of weighted advantages or disadvantages of a design solution can change the feasibility budget allocation changes. Using a practical determination when weighting performance criteria of different design solutions allow for the adequate optimal balancing in construction, while addressing also the economic limitations.

First Cost Analysis

In cases where actual cost of construction cannot be accurately accounted for, value principles or initial upfront cost becomes useful forms of analysis. First cost is the simplest form of economic analysis. The method only accounts for only costs related to the completion design and construction. First cost is linked to architectural and engineering fees, materials and systems for construction, and labour cost. This method does not account for future operating, replacement, or maintenance costs. This method also does not account for performance outcomes or the environmental impact and reuse of the completed environment. First cost as a design method has become more practical in residential construction due to increased oversight in building and energy standards seen in current practice.

This form of analysis is more applicable in projects with little budget flexibility. A flexibility bias limits the adaption of one performance standard over another due to a limiting of materials, systems, and construction methods based solely on perceived ideas of affordability. This appears to be the major limitation of first cost analysis. The using solely of first cost analysis, limits future innovation that offered through more extensive modes of analysis.

Return On Investment

Return on investment analysis expands first cost evaluation by the introduction of operation costs weighted to inflation or discount rate. This methods factors cost relative to life of the product. This method is more comprehensive than first cost analysis. The direct cost of product substitution or design changes are easily accounted for with this methodology. The limitation in this type of analysis comes from a inability to accurately account for indirect costs associated with production substitution.

Life Cycle Analysis

Life cycle cost analysis is a complex method of critical design analysis that looks at the built environment in its totality and incorporates both microeconomic and macroeconomic factors into analytic analysis models. Life cycle analysis compares the cost impacts changes in product, systems, or construction methods over the period of expected life or use. This form of analysis incorporates initials cost with all aspects affecting the owning, maintenance, and operation which occur during the life expectancy of the product or project. This type of analysis also allows for the introduction of nonnumeric qualified factors. These factors relate to the overall environmental impacts and belief structures. Life cycle analysis is applicable to every aspect of design, construction, and operating of the built environment.

Market Trends

Current markets trends place an ever expanding importance in the sustainability of construction and energy thrift of systems used in the construction of new homes and the development of new building technologies. New and improved qualities of existing materials through manufacturing advancements, along with the advancement in building sciences and research are leading professional design to methods to construct, safer, more durable, high performance housing.

Product Substitution

Product substitution is a critical operational aspect of Value Engineering, and should be accounted for in any forms of optimal analysis. Product Substitution involves the changing of one material, or system, for one of less cost. This allows the extending of budget. Materials or systems which are substituted are assumed to equally suitable for purpose.

Limitations To Product Substitution

The greatest limitation to product substitution is in the inability to accurately account for indirect costs. These costs are linked to operation, maintenance, and replacement costs. A change in material or system may also have a increase in labour costs, both direct and indirect.

Mathmatical Methods

Mathematical programming uses symbolic analytical methods to iterate and resolve an optimal solution form a field of possible solutions. *"The analytic method is concerned with the moving of existing solutions to improved ones, until no better solution can be reached."* (Gero and Radford, 1988) This process of iteration is the basis for linear programming techniques of optimization. This method involves the defining of decision variables, constraints, and a function which is be optimized, known as an objective function. *"This method allows the return of an optimal solution in a fixed number of iterative steps."* (Gero and Radford, 1988)

Linear Progamming

Linear programming offers to provide insight to cost patterns and trends which affect the overall success of the built environment. The adaptation of linear methods allow the use of most numerical and qualified variables represented in critical architectural design.

The main limitation to using linear methods is the need to accurately define appropriate system variables and parameters in order not to result in a biased solution. Application of operational methods on current forms of preferential models may correlate expressed economic concerns in advance to the design process.

Simplex Methods

Simplex optimization provides the optimal method for solving linear equations presented by critical architectural design. The Simplex method of solving linear programming problems returns a optimal solution in to a user defined objective function by iteration of designer selected decision variables. This performed by means of Gaussian reduction and back substitution to return a final optimized tableau in echelon form.

The automation of this numerical method of design optimization is easily implemented and performed by digital computation. The automating of modeling in this manner allows for an accurate level of analysis across thousands of input variables and constraints

Application of linear programming in architectural design can provide an advanced insight to cost patterns and trends that affect the overall quality and success of the built environment. Further adaption of current methods of modeling through linear programming in methods described in this study would allow the introduction and critical analysis of most variables representative of the built environment and architectural practice

Optimal Conditions

- *Budget at a maximum potential*
- *Budget at a minimum potential*
- *Maximum use of material*
- *Conservation of material*
- *Design based on availability of material*

Performance Criteria

Optimal Philosophy

This study is the application of optimal design methods applied on domestic residential construction. The emphasis is on the evaluation of existing methods and tools for optimization and the development new adapted methods. The basis points which must be meet are, a value of economy in design, construction, and operation, the ease of construction, the sustainable nature of construction, and the overall security provided in the built environment.

Economy

Systems selected for construction should use a practical commons sense when selecting affordable materials that would be common to the average individual. Economy should be maximized through careful application of budgetary concerns through understanding of limitations and client concerns. The delivered building should offer the greatest return on investment possible to client. Projects should be done in a manner that minimizes the affects of broad macroeconomic market affects.

Buildable

Selected systems should maximize the efficiency of building construction through the minimizing of components needed in construction. Delivered building should have the lowest possible occurrence of needed maintenance, repairs, and component replacements over the useful life of the building. Construction should have some form of modularity through materials and standards use. Delivered building should account for the need for future expansion and retrofits; these should be performable with the greatest amount of ease with the less amount of cost. Erection of building should be able to be performed by any local contractor. Delivered buildings should meet or exceed residential building codes. These functions can be performed through the evaluation of new and existing residential construction methods.

Sustainable

Sustainability defined: the limiting of waste in construction and the minimizing of energy consumption in construction and operation of the built environmental. Materials and systems selection should be based off durability, with the characteristics of longest life and lowest maintenance. Product sourcing should use local suppliers as much as possible out of a sense of greatest economy. Savings in construction is done through the minimal application of durable materials.

Secure

Residence need to display the highest level of protection from environmental and social hazards possible. An understanding of the reasonable care should be applied and practiced. The application of the durable materials and systems should minimize rate of hazards

Simplex Methods

Application To Testing Models

Optimal Conditions

Maximizing of A budgetary Limit

Maximization of Material Quantity

This method provides the maximum utilization of client or project budget. This is performed by the changing of design or construction methods, or by product substitution and or, changes in performance criteria. Optimality is achieved by accounting for numerical variables of materiality and construction cost subject to budgetary limit.

Minimizing Of A Budgetary Limit

Conservation of Material

This method provides a savings in material by minimizing waste.Optimality is achieved by adapting of design and construction methods by imposing limits on material use.

Design Based on Availability of Material

This method maximizes the final composition built environment by use of material availability. Optimality is accomplished by effective use of material subject to quantity limits.

Defining Of Test Assembly

To simplify initial testing a symbolic model was used. A typical wood frame wall assembly with a finite numbers of components was selected. A preferential method was used in the selection of material sub-types for each assembly components.

The selected assembly has three primary components, two by four inch nominal wood or engineered stud, half inch nominal thickness sheathing material, and two and one half inch decking screws. Data reflecting each of the materials properties is then entered into the model. This data records the size of product, unit cost, and quality or grade. During testing it was assumed that the varying material selected for each assembly would be equally suitable for purpose and offers an equal state of value or utility.

Automation of Simplex Methods

The automation of this numerical method of design optimization is easily implemented and performed by digital computation. The automating of modeling in this manner allows for an accurate level of analysis across thousands of input variables and constraints.

Description Of Modeling

Testing and modeling was completed using Microsoft Excel and Solver application. An interactive model was coded using Visual Basic for Applications (VBA) allowing for automation of the iterative process. This allows the benefits of providing a user interface and built in numerical functions which can be called by the user on demand. This also allowed for the storing and recording of determinant and derived data relating to a model function within the model itself. This data can be called for use in future model configurations, simulations, or as a benchmark for post design evaluation.

Properties of each selected material sub-type and defined user constraints are then entered into a series of tableaux or matrices for utilization during simplex iteration. These tableaux display key variables of model parameters, unit cost, minimum quantities needed to complete the assembly, budgetary allocations. The tableaux will also display after reduction, final cost per material, final quantity of each material, or maximum or minimum of a final product. Data is entered and recorded by macro functions called by the user.

The testing model allows for the entry and optimization of three assembly variations at a time, as assembly A, B, or C. This was done to better define a singular field of optimal solutions, allowing quick reference of optimality changes due to material or cost variations

Optimization By Solver Application

Optimization in the model is performed by the use of the Solver application. Model defining parameters are entered into the application from model properties in the tableaux as either as a decision variable or constraint. The application allows for the optimization of an objective function at a maximum, minimum, or user defined target numerical value. The application once started will find either an optimal solution or return an error message. An observed limitation of the Solver application identified during testing was in a form of numerical bias. This was the result of selection of inappropriate variables or constraints. If this condition exists, Solver will converge at a local minimum and provide a biased solution. Testing was completed assuming that model is linear and nonnegative.

Description of Tableau Function

Final Cost Tableau

The total final cost tableau should display after reduction the final cost of each material at a finial quantity at either a maximized or minimized quantity at a budgetary limit. This tableau is read from left to right, and total cost of the assembly can be found by the sum product of each material type final cost. This tableau is subject to budgetary limit, budget allocation per material, the minimum or maximum of material at a selected percentage, and material per unit cost. After reduction this tableau should display a final optimal cost per each component.

Quantity Tableau

The quantity tableau should show the final quantity of each material selected or needed for construction of an assembly. This tableau is subject to budget total, material budget allocation at a selected percentage, and a maximized or minimal material quantity limit. After reduction this tableau should display the optimal quantity of each material subject to defined constraints.

Quantity Limit Tableau

The quantity limit tableau is set as a lower limit of each material component needed to complete the construction of the assembly. This tableau is subject to lower quantity limits and is user defined. For testing quantities needed were three sheet of half inch plywood, eight two by four studs, and 144 mechanical fasteners. This is a user defined tableau and is static and remains unchanged after reduction.

Material Budget Allocation Tableau

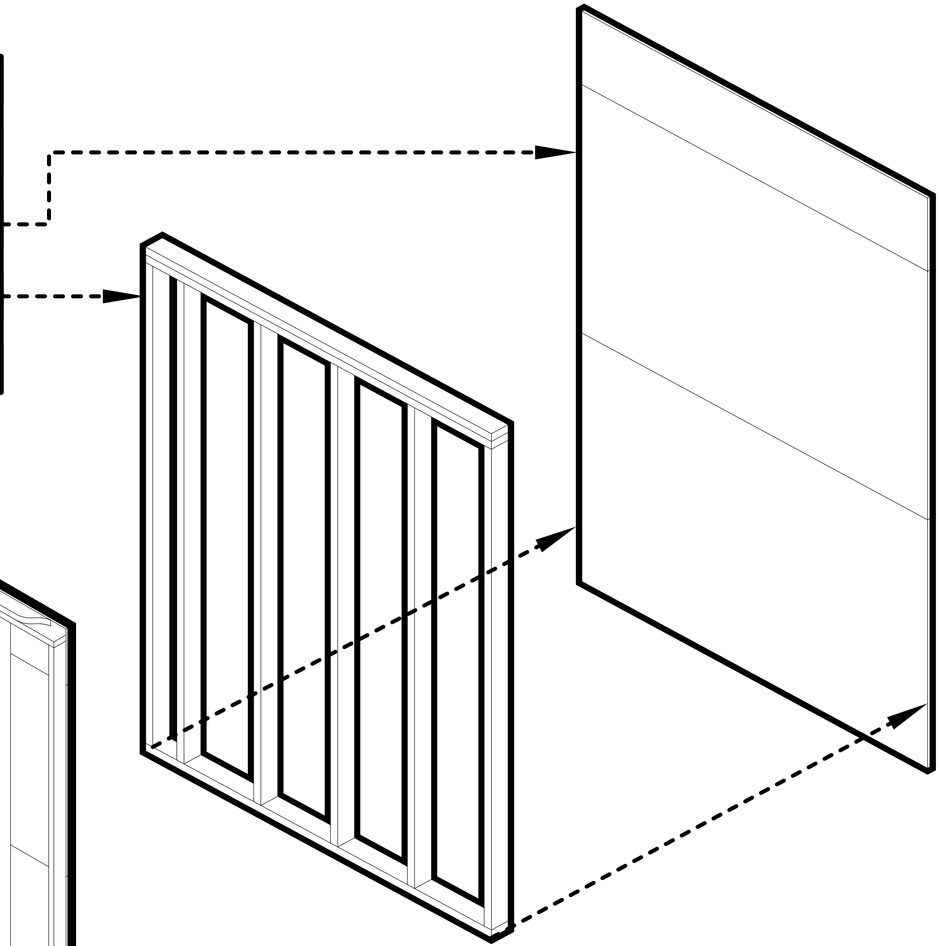
The material budget allocation tableau should display budget per material subject to a user defined percentage allocation. This percentage is required to be high enough to meet minimum requirements of material quantity. This table is solely used when maximizing material to a budgetary limit and not used for a minimal material per budget calculation. It was observed that a weighting of budget per individual material was needed to address mathematical bias due to price point. It was found without the limiting of budget per material, that modeling would favor lower cost or easily dividable price points. This tableau is subject to budgetary limit, material lower quantity limits, and material unit cost. This tableau is user defined and remains unchanged after reduction.

Unit Cost Tableau

The unit cost tableau should display the unit cost per each selected material. These costs are representative of local supplier cost and are entered by user defined preferences. This tableau is used in the calculation of final cost total, material budget allocation per material, and final cost of a maximized of minimized quantity per each material. Data in this tableau is entered from stored price data. This tableau is user defined and remains unchanged after reduction.

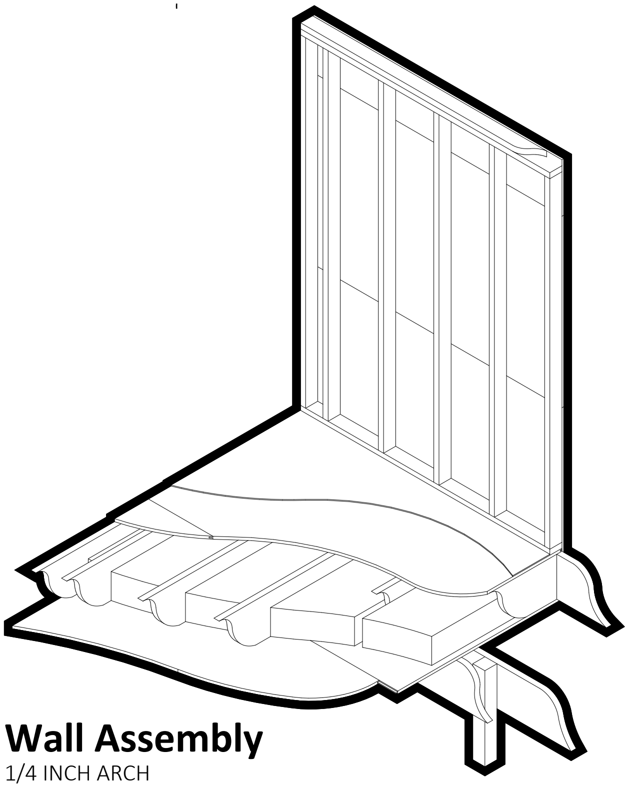
Test Assembly

Material Table	
Type	Quantity
1/2" Plywood	3
2X4 Studs	8
2-1/2" Screws	144



Exploded View

NOT SCALED



Wall Assembly

1/4 INCH ARCH

Maximizing of A Budgetary Limit

Material Maximized by Optimal Iteration

Maximization of Material Quantity

This method provides the maximum utilization of client or project budget. Optimality is achieved by accounting for numerical variables of materiality and construction cost subject to budgetary limit.

This method is the most common scenario that a designer, contractor, or tradesman, will encounter is the fitting of construction or system to a budgetary limit. This Budgetary limit can be either a maximum or minimum target.

Description of Method

Using the wall assembly as the testing model, optimal related conditions would occur at material maximum with the highest rate of budget utilization.

Application of Method

This method will produce a maximum optimal material quantity at a budgetary upper limit, subject to material quantity lower limits and budgetary upper limits.

It should be noted that care should be practiced in the selection of proper constraint or model variables. Weighting is required with this method of simplex reduction in order to resolve at an unbiased optimal point. Without the weighing of budget, reduction will resolve at a local minimum, or favor materials with lower cost with easily dividable numerical values. Weighing is achieved by the allocating of budget per material.

Model At Maximum

Objective Function *Less than equal to buget maximum*

$$Px+Sx+Fx \leq \text{Budget Maximum}$$

Subject To *Greater or equal to material lower limits*

$$Px \geq Pq$$
$$Sx \geq Sq$$
$$Fx \geq Fq$$

And *Less than equal to material allocation*

$$Ptc \leq \text{Plywood Budget Allocation}$$
$$Stc \leq \text{Studs Budget Allocation}$$
$$Ftc \leq \text{Screws Budget Allocation}$$

And *Less than equal to Budget Maximum*

$$\text{Budget} \leq \text{Budget Maximum}$$

Plywood	**P**
Studs	**S**
Screws	**F**
Quantity	**q**
Total Cost	**tc**

Budget Allocation

Budget material allocation can be set based on two methods, material lower quantity, and material percentage allocation.

Budget By Needed Quantity

Budget set by a minimum quantity is produced by simple multiplying of needed material by the unit cost. This will return a lower limit for the model budget.

Limitations

The issue with this method is that it can only be used to produce a minimum return. Use in maximum return will favor local minimums and return a biased optimal point.

Budget By Weight Percentage

The method will produce a maximum optimal quantity at the highest allowable rate of budget utilization. Percentages are calculated by the user based on the desired returns.

Limitations

The issues with this method are in the correct selection of budget allocation. Budget allocation will change based on case. It is however possible to use regulatory and size limitations to evaluate the budget allocation. This is the most favorable method to use to find an optimal maximum material quantity.

Results At Maximum

Budget	297 USD

Material Quantity

	Before	After
Plywood	3	15
Studs	8	48
Screws	144	212

Material Budget Allocation

	Before	After
Plywood	139.95	134.85
Studs	139.95	138.72
Screws	14.84	14.84

Budget Utilization

Plywood	96%
Studs	99%
Screws	100%

Overall Utilization	97.10%
Unutilized	2.9%

Minimizing of A Budgetary Limit

Material Minimized by Optimal Iteration

Minimization of Material Quantity

This methods provides a conservitive utilization of client or project budget. Optimality is achieved by accounting for numerical variables of materiality and construction cost subject to budgetary limit.

Application

This method will return a minimum quantity of material subject to material lower limit, and budget maximum limit. The returned budget can be at a maximum budgetary upper limit. The normal return will be below the budget maximum limit. This can demonstrate the feasibility of budget selection for one assembly over another by having a cost higher or lower than expected limits.

This method is useful in the production of lower budgetary limits which can be applied in further testing.

Model At Minimum

Objective Function *Less than equal to buget maximum*

Px+Sx+Fx ≤ Budget Maximum

Subject To *Equal to material lower limits*

Px = Pq

Sx = Sq

Fx = Fq

And *Less than equal to Budget Maximum*

Budget ≤ Budget Maximum

Plywood	P
Studs	S
Screws	F
Quantity	q
Total Cost	tc

Results At Minimum

Budget	297 USD

Material Quantity

	Before	After
Plywood	3	3
Studs	8	8
Screws	144	144

Material Budget Allocation

	Before	After
Plywood	26.97	26.97
Studs	23.12	23.12
Screws	10.08	10.08

Budget Utilization

Plywood	100%
Studs	100%
Screws	100%

Overall Utilization	20.25%
Unutilized	79.75%

Conclusion of Budgetary Methods

It was found that each of these two budgetary methods will, when correctly configured, will produce a optimal return. This return can be at either a maximum or minimum target.

Design Based on Optimal Returns

This method uses the optimal returns of cost and quantity generated by both budgetary methods. This allows the analysis of design composition to test the feasibility of budget reallocations. This is done to achieve a higher rate of utilization in the design by utilizing waste products. Waste products have the potential to increase the success of construction.

It must be noted that building products cannot be purchased in fractional amounts. Any unused materials are considered waste product if not utilized in the design.

Application

Once the defined material quantity is satisfied, any excess material or budget can be reallocated to increase design performance. This reallocation can be in the form of, material quality increases, material quantity increases, better systems or methods, or increase in building footprint.

Coverage Limits

By introducing a minimum coverage variable into modeling it allows the calculation of waste ratios based on actual purchased, and need material coverage. This ratio is subject to material quantity lower limits and a budgetary maximum limit.

The utilization of waste products can be demonstrated by using the wall assembly test unit. The needed actual amount of plywood needed is eighty sqaure feet, or 2.5 sheets. The purchased amount is ninety-six square feet, or three sheets. Each sheet is four by eight feet and has thirty-two square feet of coverage. *(see figures on page 21)*

Limitations to Reallocation

The process to utilize waste materials in the design is subject to structural and regulatory limitations. This limitation may make it unfeasible to reallocate overages without incurring cost both directly and indirectly.

Regulatory limits

The utilization of waste material and budget overages become subject to regulatory limits which define the allowable use of each material. Each material or method of construction is dependent on spacing or composition of the structure.

Results At Maximum

Budget	297 USD
Plywood Per Sheet Coverage	32 SQFT
Needed Coverage	80 SQFT
Fixed By Purchase	480 SQFT
Needed Quantity	2.5 Sheets
Quantity Fixed By Purchase	15 Sheets
Plywood Unit Cost	8.99 USD
Overall Cost	134.85 USD
Utilization	16.6%
Unutilized	83.4%

The calculated waste in the design is 400 square feet, or twelve and half sheets of plywood, at 112.38. This at a maximum cost of 288.41 dollars would be 38.9 percent of total budget. Potential exist in the adaption of design to use this overage of budgetary of material expenditure to expand design or reallocate products to other aspects in the design.

Using the wall assembly, the use of excess plywood is dependent on spacing of the studs. For a two by four inch stud this would be a maximum allowable spacing of eighteen inches on center for unrated studs. This spacing is set by code. Since spacing is dictated and not arguable, the use of plywood overage would possible result in the need to purchase more studs to allow its use. This would also result in a need to purchase more fasteners and higher labour costs, from expansion of construction

Size Limitations

Since each piece of plywood is two foot by four foot, framing will have to fall as to have framing support the edges of the plywood. Changes to use a half sheet or less of plywood will dictate a change in framing or bracing. Design should utilize the prescribed size of each material to its fullest extent when possible.

Results At Minimum

Budget	297 USD
Plywood Per Sheet Coverage	32 SQFT
Needed Coverage	80 SQFT
Fixed By Purchase	96 SQFT
Needed Quantity	2.5 Sheets
Quantity Fixed By Purchase	3 Sheets
Plywood Unit Cost	8.99 USD
Overall Cost	26.97 USD
Utilization	83%
Unutilized	16.7%

The calculated waste in the design is sixteen square feet of plywood, or half a sheet, at 4.50 dollars. This at a minimum cost of 60.17 dollars would be 7.5% of the total budget.

Limits Defined by Rates of Utilization

This method uses the rate of utilization to find dependant materials. Materials with a higher rate of utilization will dictate the use of materials with a lower rate.

Utilization Rate

Using the wall assembly test model as example, with a conservative budget, at a optimal minimum, we can calculate material utilization rates.

Since the rate of utilization for the two by four studs and screws are at 100%, the use of waste plywood is dependent to the other products. This method allows for the analysis of material usage accuracy in each design. This demonstrates any feasibility to changes.

Limitations

It should be noted that it may not feasible to utilize waste products. This method should be coupled with life cycle analysis to produce a accurate cost profile representative of design changes.

Conclusion

The method provides to be the most useful in the directing of critical architectural design. When complied with budgetary methods, it allows for the accurate accounting of both externally fixed material and regulatory exogenous variables, and designer defined internal endogenous variables. The ability to express most, if not all design variables in a single generative model, allows for the production of the highest rate of optimal returns to architectural design problems. This accuracy in modeling provides solutions sensitive to both economic conditions and waste products. The application of linear programming, in architectural design, can provide an advanced insight to cost patterns and trends that affect the overall quality and success of the built environment.

Results of Utilization at Minimum

Budget	297 USD

Material Quantity	
Plywood	3
Studs	8
Screws	144

Quantity	Needed	Fixed By Purchase
Plywood	2.5	3
Studs	8	8
Screws	144	144

Material Utilization	
Plywood	83.3%
Studs	100%
Screws	100%

Waste Values	
Plywood	~4.50 USD
Studs	0
Screws	0

References

Radford, Gero (1988). *Design by Optimization, in Architecture, Building, and Construction*. Van Nostrand Reinhold.

Robert J. Gordon(2016). *The Rise and Fall of American Growth; The U.S. Standard of Living Since the Civil War.* United Kingdom: Princeton University Press.

Kenneth Boulding(1966).*The Economics of the Coming Spaceship Earth*. In H. Jarrett (ed.) 1966. Environmental

Thomas Kuhn (1962). *The Structure of Scientific Revolutions*. Chicago: University of Chicago Press.

Le Corbusier(1931).*Towards a New Architecture*. London: John Rodker

Frank Lloyd Wright (1941).*Frank Lloyd Wright on Architecture: Selected Writings, 1894-1940.* New York, New York:Duell, Sloan and Pearce.

Frank Lloyd Wright (1943).*Frank Lloyd Wright an Autobiography*. New York, New York:Duell, Sloan and Pearce.

Site: https://www.bea.gov Accessed September 2017
Site: https://www.census.gov Accessed September 2017