Developing a Calculator for Evaluating Physical Design Characteristics and Whole House Performance: A Preliminary Method

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Developing a Calculator for Evaluating Physical Design Characteristics and Whole House Performance: A Preliminary Method

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The authors accept responsibility for the report and any shortcomings it may have.

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Disclaimer:

Preface:

Comparing the characteristics of one house to another is one of the most difficult tasks facing a prospective homebuyer. Each house is the result of tens of thousands of decisions made by material suppliers, product manufacturers, designers, engineers, regulatory officials, marketing professionals, builders and subcontractors. Even though many appear similar, each house is effectively unique, a one of a kind assembly that will stand, breathe, manage water and shelter it's inhabitants differently.

Professionals designing the house, selecting the materials and products to include and developing the processes used to design, engineer and produce the house face a daunting number of choices as well. Their choices affect how quickly the market accepts the house, how the house behaves when stressed by forces of nature and how efficiently the house uses energy, labor, and materials.

"Developing a Calculator for Evaluating Physical Design Characteristics and Whole House Performance: A Preliminary Method" has made the first steps towards developing a tool for prospective homeowners and professional housing providers to systematically consider the many "what if" scenarios common to residential construction in the United States. This tool is a calculator that takes the inventory of the processes, products and materials used to design, engineer, and construct a house.

The calculator uses performance scores for each characteristic of the house and the processes used in its design and construction. These scores are then modified by the values of the prospective homebuyer or builder and further modified by the way the construction materials and processes interact with each other to arrive at a "whole house score." In this way, the calculator allows for "what if" comparisons. The user can consider the effect of a professional architect on the whole house just as the builder can consider the effect of a formal quality assurance program.

This project is the first step towards making a tool that may become a simple website, or a "smart agent" working within a home's building information model.

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Executive Summary:

"Developing a Calculator for Evaluating Physical Design Characteristics and Whole House Performance: A Preliminary Method" grew from two research projects "Creating Whole House System Solutions" and "Designing Whole House Solutions." The purpose of these projects was to investigate the feasibility of quantitative assessment of the performance of design and production processes, materials and systems, and the interaction between them for the purpose of comparative scoring in the context of characteristics valued by prospective buyers, builders, or other stakeholders involved in residential construction.

The framework for this calculated score is an adaptation of the Environmental Evaluation System (EES) developed by the Battelle Laboratories for systematically assessing the impacts of alternative projects. This method has been used successfully to evaluate complex problems from differing points of view.

As adapted for residential construction, the framework identifies System Choices, construction materials and processes, that makeup the house in question. These include the extent of professional design and engineering involvement in the specific house, the quality, safety and production systems employed by the builder, as well as the physical materials, components and subsystems that make up the house. Experts score the performance characteristics and interactions between the System Choices, considering the climate, wind exposure, seismic conditions and regional building trade practices for the specific location of the house. The performance score for each System Choice is established in the context of specific criteria and alternatives for that System Choice. The interaction between each System Choice making up the house is subsequently scored to reflect the positive or negative influence of one System Choice upon another.

Users of the calculator complete a form to rank the relative importance of performance characteristics such as: a comfortable home, a healthy home, a dry home, a sturdy home, a safe home, a flexible home and an efficient home. This ranking is used to weight the performance factors and subsequently applied to the interaction scores. Scores for each house characteristic are then totaled to arrive at the whole house score.

It is hoped that future development of the whole house calculator will automate the process to a point where a prospective buyer, builder or realtor could log on to a website, answer a questionnaire and be presented with a list of homes ranked by conformance to the user's desires as described in the questionnaire.

Part 1: Whole House and Systems Design

Comparing one house to another, like comparing one innovation to another, is a difficult task for both prospective homebuyers and builders. The comparisons frequently include objective data such as reductions in heat transfer or enhanced durability, but these comparisons also frequently require subjective analysis, such as, "how important is reduced heat transfer or enhanced durability to me or my customers?" Even if two alternatives have enough data of a similar format to allow for direct comparison, the larger issue of the positive, neutral or negative effect, of the innovation or change on the larger system remains.

This report documents the initial efforts to develop a tool, the whole house calculator, designed to help prospective homebuyers and homebuilders account for objective and subjective factors involved in making complex comparisons between homes, or between alternative processes, materials, components and systems.

Since the early 1970's, methods for quantitative scoring of objective and subjective factors involved in environmental projects with complex technical alternatives and social implications have been used to assess the overall impact of environmental projects. These methods have been adapted to allow for a similar scoring of quantitative and qualitative factors involved in comparing the performance and interactions between the processes, materials, components and systems found in residential construction.

Conventional Building Approach vs. Systems Approach

A house is a product of almost two hundred years of trial and error development by inventors, amateurs and professional builders that have added and subtracted materials and subsystems to the house in response to changing technological, social and financial pressures. Over the last forty years some individual subsystems have been carefully scrutinized, researched, and optimized to balance performance outcomes with financial inputs, but most continue to be based in traditional approaches that have evolved over time. The result is a collage of semi-independent systems of design, engineering, procurement and production, each having discrete standards, goals, and governing regulations. The intense focus on discrete system optimization has, in some highly visible cases, produced unexpected interactions with related or adjacent systems that have significantly compromised the integrity of the house as a whole. The confluence of innovation with a traditional approach to housing design and construction seems to be a common factor in these instances.

The conventional building approach can be described as a series of innovations applied to a traditional construct. Builders often adopt a traditional approach to the processes, products and designs for the house to be able to focus on the production and sale of the house. Traditions are familiar, don't require extensive design or analysis that costs time and money, and generally, are safe in the marketplace.

Some of the traditions have developed from personal success, while some have been handed down as best practices. Traditions are often perceived as having been established by tried and true methods and require no further investigation.

Traditions seldom provoke innovation, but the competitive marketplace demands it. Financial and legal risks temper the extent of innovation proposed by builders, and accepted by buyers. New processes, materials or products are typically introduced into the traditional process slowly, in small increments, adding a new material or system or substituting for an old one.

Often this substitution is done without full consideration of its impact on related parts of the system or the whole. The innovation is introduced to the market often based on the reputation of its advocate. The better the reputation of the advocate, the greater the capacity to share risk with the builder or buyer.

A systems approach stands in contrast to the collage of components produced by the traditional approach. One of the many definitions of a system is “a dynamic entity, like a cell, organism, organization or environment which is comprised of interdependent parts, fundamentally characterized by inputs, processes or throughputs and outputs; parts in interrelationships that work together for the purposes of the whole.”[1]

The phrase “whole house” implicitly suggests all parts working for the benefit of the whole. The house itself is simultaneously the result, or output, of a much larger system and once completed, it is, a system itself.

Because a house is both the output of a system and a system itself, the concept of wholeness of the house extends beyond its walls. So to consider a whole house is to consider both its completed end state and the processes that produced it.

Interrelatedness is a defining aspect of a system. The degree of interrelatedness of the parts and processes that constitute the system effectively set the level of performance of the system and the products of the system. Theoretically, all parts and processes interact with and affect all other parts and processes in the system as well as the environment in which the system is located.

Why a systems approach is important

As a dynamic entity, a house comprises interdependent parts. It is critical that the specifics of interdependence between parts be known, and that the interdependence be designed for the success of the whole, not just the part. This designed interdependence, optimized for the success of the whole, is the defining characteristic of what will be referred to in this report as the “whole house” approach.

A systems approach is the most useful method to structure cycles of analysis and synthesis toward achieving a set of goals.

A search of the literature was conducted to assess the whole-house design approach for residential construction. Dozens of interactions that negatively or positively impact the performance of homes have been documented in the literature, but these interactions are rarely considered during the design or

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1 Extracted from http://www.changezone.co.uk/glossary/glossary.html

construction of homes. The following section summarizes the interaction opportunities, performance standards for various systems and subsystems, and past and ongoing efforts at a whole-house approach in the housing industry. More detailed information on the literature search findings is provided in Supplemental Data #1 through #5, produced as separate reports.

One recent example of a systems approach to residential construction that exemplifies the "whole house" approach has been developed by Pulte Homes' research and development group, Pulte Home Science (PHS).

Pulte identified critical goals for the system:

- Speed, quality and durability of construction;
- Simplicity of field processes;
- Thermal and moisture management performance; and
- Mass customization.

Reduction in the number of parts and connections became the key strategy to achieve these goals. Construction is simplified by using larger, more precise parts with fewer connectors required in field processes.

All systems in the house were considered under this strategy. This stands in contrast to simply applying prefabricated panelized wall structures to existing foundation, insulation, and floor framing technologies. Previous studies have shown that the interface between the innovation (wall panels) and the unchanged systems (foundations, utilities) is frequently the cause of conflicts that ultimately degrade the performance of the innovation and in some cases, the original system itself (O'Brien, et. al. 2002).

By considering all components of the system, including information exchange, procurement and labor, interfaces between subsystems were designed to connect with a degree of precision that enhanced both speed and accuracy in component plant and field operations.

The major elements of Pulte's redesigned systems process are:

- Cross-domain integration of information;
- Web based process scheduling;
- Parametric CAD modeling;
- Numerically controlled fabrication tools;
- Just-in-Time component delivery; and
- Cross-trained field labor.

The major components of Pulte's redesigned house system are:

- Crushed rock footing bed;
- Precast concrete foundation walls;
- Prefabricated trussed floor panels;
- Prefabricated wall panels with windows pre-installed;
- Prefabricated light gauge steel interior partition framing; and
- Prefabricated roof trusses.

The ability to modify these components in order to meet the goal for mass customization required Pulte to produce the components themselves. A special component production facility was developed to fabricate, label, and ship the components to each construction site using Just-In-Time, (JIT) techniques adapted from manufacturing industries.

Production of the precast foundation walls, prefabricated trussed floor panels, and prefabricated wall panels with preinstalled windows required extensive process engineering and tooling design extending to the design of the racks and trailers used to ship the components to the jobsite.

In the component plant, parametric CAD designs are batched by a central scheduling application to control the day's production. Houses are not produced as a complete kit of parts, as the time required to layout, set foundations, first story floor, and walls would expose the second story floor and wall components to the elements for an undesirable period of time. The scheduling application keeps track of all project progress in the field and produces parts for each project as necessary for JIT delivery.

On the plant floor, laser layout tables are driven by the CAD information to guide the location of bulkheads, inserts and holdouts in the foundation formwork. Numerically controlled inventory processes maintain a JIT relationship with suppliers of raw materials for the foundations, floor panels, wall panels and partition framing. The central process controller schedules delivery of large-scale oriented strand board (OSB) panels and steel truss components that will be used to assemble floor trusses, while the CAD information guides the numerically controlled tooling to assemble the panel, and precut holes for HVAC ducts and registers in the floor.

Wall panels are similarly developed. Large-scale structural wood panels are pulled from inventory, squared and delivered just in time for the numerically controlled machine to pick them up, and place them on a moving assembly table where adhesive is laid down, insulation panels with integrated electrical raceways are dropped onto the adhesive, another layer of adhesive is sprayed over the insulation, and a face of the same large-scale structural wood paneling is installed. The assembly is pressed together, and then a numerically controlled router cuts out rough openings for doors and windows. The panel moves to a vertical rack where flashing and the window unit are installed. Finally, the panel is labeled and readied for shipping.

Light gauge steel partition framing is fabricated at a workstation fed by a large coil of galvanized steel roll formed into steel studs, precut to length from CAD information, and assembled into interior partition panels. Throughout the plant, inkjet printers label the components with project, location, and component identification, to increase field erection accuracy and speed.

The roof trusses are procured through an independent fabricator as the degree of customization, accuracy and just in time delivery needs for this component are widely available. In plant production of these components would not yield tangible benefits.

Overall the system developed by Pulte Home Science is one of the most significant developments in the systems approach to housing since the Lustron home development after the Second World War.

Part II The Whole House Calculator
Approach and potential uses:

The PATH Whole House Roadmap 2003 Progress Report identified the need for a design tool capable of addressing multiple parameters to support optimization of the design and production process in housing (Newport Partners 2003). The report further calls for the tool "to allow designers to evaluate different scenarios with each subsystem to converge on the most efficient overall design based on a set of objectives defined by the user."

There are approximately 143 separate parts - stud, joist, nail, drywall sheet, shingle, etc. - that make up the 54,000+ total part count in a house. (O'Brien 1999) Given that there are at least four alternatives for each part, and taking the six climate zones and six seismic design categories identified in the International Residential Code (IRC), and conservatively assuming six alternative house designs facing one of eight possible compass orientations there are over five hundred million combinations of the system (Appendix 1).

This large number of choices poses a considerable barrier to each builder or buyer applying a fully rational approach to the construction or purchase of a house. Given that many builders or buyers are not considering houses in multiple climates or seismic categories, the problem becomes a bit simpler, only fifteen million possible combinations (Appendix 1).

This large number of choices, and the resulting difficulty a builder or buyer faces when evaluating a course of action is not unlike the difficulty citizens face when evaluating alternatives for large projects that have the potential to interact positively or negatively with the natural and cultural environment.

Battelle Laboratories has developed a method to quantitatively compare complex alternatives based on their characteristics, performance and the value citizen-users place on certain outcomes.

The Battelle Method

The "Battelle Columbus Laboratory" in the United States developed the Battelle method, originally called Environmental Evaluation System (EES) (Martel and Lackey 1997). This method is employed to compare alternative projects through the systematic evaluation of their environmental impacts. Based on the comparisons, the best alternative project or the one less degrading to the environment can be chosen. This method has been frequently used in the assessment of projects for water resources, roads, nuclear plants and other projects.

The Battelle method lists 78 environmental, social, and economic parameters according to their importance, varying from 1 to 1000, and estimates of quality of environment in relation to each parameter. Environmental quality is adapted to a scale ranging from 0 to 1. In this method, human environment is assessed from four points of view, namely ecology, physical and chemical factors, aesthetic factors, and human and social interest. These four factors are divided into eighteen components and the components are further subdivided into 78 parameters. The method is then applied in the following three steps:

1. Arranging categories, components and parameters according to their importance in decreasing order.
2. Estimating the relative coefficients for the importance of each category, from 0 to 1.
3. Establishing a relationship between each parameter and environmental quality based on previously generated curves.

The environmental impact for each parameter can be generated by multiplying the figure related to the importance of the parameter with its estimated environmental quality. By comparing the balances for each project, the most environment-friendly project can be determined.

The Battelle method has apparent drawbacks, which incurred many criticisms. It does not point out which of the social groups are influenced nor does it require the participation of the community. It is difficult to understand despite a comprehensible end-result and it requires data and sound knowledge on a wide range of subjects. Because of the data needs, the method requires considerable investment, especially if nearly 78 parameters are to be examined. However, this method has its advantages in systematically evaluating environmental impacts of alternative projects based on holistic parameters. It is a good method for environmental evaluation if properly applied.

Translating the Battelle method

The Battelle method for environmental evaluation does not directly translate for use in the whole house calculator, but it is a useful model for approaching the problem of weighting and quantifying both objective and subjective aspects of a complex project and generating a score that can be used to compare one set of project characteristics with another.

Also like the Battelle method, the whole house calculator is dependent upon a large body of technical expertise to establish both of these scores.

Unlike the Battelle method, the whole house calculator operates on a more closed system, considering approximately 543 system choices to the many processes, systems, and components in residential construction. (Appendix 2) The system is considered “more closed”, not absolutely closed because the residential construction industry continues to innovate and introduce new materials, processes, and components, like the commercial construction industry.

Given this more closed state, it is possible to gather expertise to establish consensus scores for performance and interaction of each alternative. These scores have been assembled as the database of performance and database of interaction scores to support a simple, web-deployed calculator.

Like the Batelle method, the whole house calculator uses the scores from 70 to 90 Systems Choices in two stages. First, a raw assessment is made of the performance of each System Choice in the context of the other Systems Choices comprising the house. Weighting factors reflecting the relative levels of importance of the subsystems to life safety are applied to the primary subsystems. Second, the interaction of each System Choice on each of the other System Choices making up the house is scored. Third, performance scores are multiplied by interaction scores to adjust the performance of each

Systems Choice, and finally, each Systems Choice is multiplied by the user-weighting factor to reflect its importance on the outcome desired by the user.

Part III: Structure and Description of the Whole House Calculator

Functionally, the calculator is a pair of databases driven by lookup functions. The first database is filled with performance scores for each System Choice for a process, material or component. The second database is filled with the scores for the interactions between the System Choices. The lookup functions are configured to extract data from these databases by one or two input forms. The following section describes the major elements of the calculator.

User Values

Users of the calculator, whether they be homebuilders or homebuyers, must first identify the attributes in a house that are most important to them. This is reflected in the Calculator by the User Values. The User Values is a listing of attributes that the user can set by order of importance. There are different User Values for homebuilders and homebuyers.

The User Values for homebuyer are:

- Comfort:
  - Temperature;
  - Load responsiveness;
  - Humidity;
  - Air velocity.
- Dry:
  - Bulk moisture management;
  - No mildew;
  - No mold.
- Efficient:
- Flexible:
  - Change during construction;
  - Small Office Home Office;
  - Aging;
  - Multiple households;
  - Do-it yourself.
- Health:
  - VOC emissions;
  - Dust;
  - Particulates;
  - Fibers;
  - Air quality.
- Safe,
  - Fire detection;
  - Suppression;
  - Egress;
  - Fall hazards.
- Sturdy:
  - No visible deformation;
  - No envelope breach in 100 year events;
  - No damage from 50 year events;

The User Values for the Builder are:

- Clear:
  - Intuitive assembly;
  - Minimizes number of parts;
  - Minimizes number of processes;
  - Minimizes number of tools;
  - minimizes special tooling.
- Durable:
  - Reduction of moisture sensitivity;
  - Minimal shrinkage or distortion;
  - Chemically inert - minimally reactive;
  - U/V resistance (to plasticizer loss / embrittlement, color change);
  - Corrosion resistant;
  - Minimal chemical interaction;
  - Minimal outgassing;
  - Minimal galvanic interaction;
  - Biologically inert;
  - Doesn't provide foodsource for microorganisms;
  - Minimizes habitat for microorganisms.
- Efficient:
  - Minimal / no material waste;
  - Minimal / no labor waste;
  - Quickly constructed;
  - Easily available materials across geographic regions.
- Flexible:
  - Able to adapt to changes in

supply source;
  - Able to adapt to "in-process" owner changes;
  - Able to adapt to variety of owner profiles (age, cost, family).
- Moisture Response:
  - Doesn't leak;
  - Doesn't trap water;
  - Designed for long term drying;
  - Avoids vapor entrapment;
  - Contributes to assembly draining;
  - Contributes to assembly drying;
  - Minimal / no damage from incidental wetting.
- Predictable:
  - Makes dependable substrate for subsequent processes;
  - Maximizes quality;
  - Maximizes precision;
  - Repeatable quality.
- Safe:
  - From exposure to hazardous materials;
  - Having a minimal content of soluable / friable heavy metals and inorganic fibers;
  - Integral safety characteristics (anchorage for fall restraint, minimize trench time..);
  - Minimal inherent exposure to trip, fall hazards, dust & noise production;
  - Minimal exposure to repetitive stress and ergonomic overstress;
  - Process design safety (temporary loading, rigging, cuts, abrasions, blood exposure, fall hazards).

The Calculator user is asked to distribute one hundred points across the User Values according to their importance to the user. These User Value Weighting Factors (*Uw*) become percentage multipliers to the performance scores of the System Choices constituting the house in question.

Subsystems and Subsystem Weighting

The house functions are broken down into subsystems in order to group parts having a similar performance expectation placed on their design, specification, installation and in-service behavior. These subsystems further reflect the major activities and subcontract groups that make up the construction process.

Weighting factors are applied to reflect the importance of the role each subsystem plays in the function of the house as well as the health and safety of the occupants.

Subsystems

- Process & production design
- Foundation
- Superstructure
- Envelope
- Interior partitions & finishes
- Millwork
- Utility distribution
- Electrical power & light
- Sewer & water
- Thermal systems

As with the User Values, the Subsystems Weighting Factors total 100. These Subsystems Weighting Factors (*Sw*) become multipliers to the performance scores of the System Choices to reflect the importance of their role in the whole house.

Weighting factors for houses in different geographic regions reflect the importance of a subsystem's performance in the particular climate. Seismic intensity, wind exposure, termite infestation and radon levels require the development of additional weighting factors at the county level of detail, similar to the International Building Code's approach to identifying risk levels for radon.

System Choices

The System Choices represent a comprehensive listing of every process, material and component choice that went into the building of the house. The specifications of the house should provide the majority of the information. Additional design and production process information, such as if an architect was employed, the type of quality process employed by the builder, etc., should be readily available. Appendix 2 lists the Systems Choices as developed for the calculator to date.

Performance Scoring

Each System Choice is then scored on a scale of 1 to 5 with 1 assigned to the lowest performance System Choice, and 5 to the highest performing System Choice for each of the following Performance Issues:

- Moisture / Vapor Control;
- System Integrity;
- R-value;
- Reduce Cooling Load;
- Reduce Heating Load;
- Increased Comfort Level;
- Reduced Air Infiltration;
- Indoor Air Quality;
- Chemical Compatibility & VOC;

- Resists Mold/Mildew/Insects;
- Supports Physical Integration with Other Systems;
- Reduces System Part Count;
- Capable of Engineered Performance;
- Regional Trade Familiarity;
- Part of Overall Quality System;
- Reduces Construction Time;
- Increases Construction Precision;
- Reduces Number of Subcontracts;
- Reduces Construction Cost (labor and material);
- Durability / Low Operating Cost;
- Provides Initial Design Flexibility;
- Provides Maintain-it-Yourself flexibility;
- Reduces Environmental (energy, waste) Impact.

The sum of the System Choice's scores for each of the above Performance Issues becomes that System Choice's Performance Score (*Ps*).

Interaction Scoring

Interaction Scoring is the rating of the degree and net effect of the interaction between each System Choice. The Interaction Scoring is scaled from –3 to +3 depending on the resulting interaction. Interactions Scoring breaks down as follows:

- +3, where the interaction would likely result in a major improvement of the performance of the two System Choices;
- +2, where the interaction would likely result in a substantial improvement of the performance of the two System Choices;
- +1, where the interaction would likely result in a some improvement of the performance of the two System Choices;
- 0, where there was no substantial interaction between the two System Choices;
- -1, where the interaction would likely result in a some degradation of performance of the two System Choices;
- -2, where the interaction would likely result in a substantial degradation of performance of the two System Choices;
- -3, where the interaction would likely result in a major degradation of performance of the two System Choices.

The sum of a System Choice's scores for their interaction with every other System Choice in the house becomes that choice's Interaction Score (*Is*).

Developing the Performance Factor:
The Performance Factor is the total of the Performance Score for a given System Choice multiplied by the weighting factor for the subsystem to which it is normally associated. The resulting value is further multiplied by the User Weighting Value most closely associated with the given system choice.

The calculation begins by multiplying the Performance Score (Ps) by the Subsystem Weighting Factor (Sw). The resulting product is multiplied by the User Value Weighting Factor (Uw) to arrive at the Performance Factor (Pf).

$$Pf = \left((Ps \times Sw) \times Uw \right)$$

Developing the Interaction Factor:
The Interaction Factor is the reciprocal of the sum of the horizontal and vertical interaction scores of a system choice in the interaction matrix divided by the Total Variance. The resulting value is subtracted from 1 to normalize negative scores.

Taking the reciprocal and normalizing by subtracting from 1 are steps taken to make the resulting interaction factor appropriately enhance or diminish the performance factor. The advantage of this approach may be best demonstrated with the following example:

- Assume a given Systems Choice had a Performance Factor of 62.5, and a Interaction Score of -.04, multiplying the interaction score, -.04, by the performance factor, 62.5, yields a net score of -2.24. This effectively says that the negative interaction completely overrides the performance score. This seems to be an unreasonable assumption given the level of performance the current housing stock is achieving.
- Using the same Performance Factor and Interaction Score, we normalize the negative interaction by subtracting it from 1. This converts the -.04 interaction score to a Normalized Score of 1.04. Multiplying this by the Performance Factor yields a net score of 64.74. This effectively says that a negative interaction increases performance, which most would agree is unlikely to be the case.
- Using the same Performance Factor, Interaction Score and taking the reciprocal of the Normalized Score, 1/1.04 yields .97 which, when multiplied with the Performance Factor of 62.5 equals 60.34. This is effectively saying that a negative interaction reduces performance, but does not reduce performance to zero, which is a proportional reflection of the impact of a negative interaction. The more negative an interaction is, the more performance is reduced.

Developing Total Variance:
Total Variance is the total number of points existing in the range between the maximum positive Interaction Score and maximum negative Interaction Score possible for the Interaction Score of a given Systems Choice.

If there were 94 Systems Choices describing a house, the 94 Systems Choices would be listed on a vertical axis and a horizontal axis to make the interaction scoring matrix. The interaction of each System Choice with each of the other 94 System Choices is scored on a scale from +3 to -3 to indicate the degree of enhanced or degraded performance likely to result from this particular interaction. The highest possible Interaction Score for any one System Choice is 93x3 or 279 points. The lowest possible Interaction Score for any one System Choice is 93x-3 or -279. There are 558 points in the range between +279 and -279 making the total variance 558 points.

Subsequently, the Interaction Factor (If) is calculated as the reciprocal of the sum of one minus the quantity of Interaction Scores (Is) divided by the total variance (Tv) for the Interaction Scores.

$$If = 1 \div \left(1 - \left(\sum Is \div Tv \right) \right)$$

The Whole House Score:
Finally, the Whole House Score (Whs) is calculated as the sum of the products of the Interaction factor (If) multiplied by the Performance Factor (Pf).

$$Whs = \sum (If \times Pf)$$

The calculator process is summarized as nine steps:

1. Use outline specifications or CAD files to extract alternative system characteristics from database.
2. Use the resulting set of System Choices to configure lookup functions and extract Performance Scores from database.
3. Use the same set of System Choices to configure lookup functions and extract Interaction Scores from database.
4. Multiply Subsystem Weighting Factors by the appropriate System Choices Performance Scores.
5. Multiply User Value Weighting Factors by the System Choices Performance Scores.
5. Calculate Total Variance as the range of points between the sum of perfect scores (+3) and the sum of imperfect scores (-3), applied to all System Choice interactions.
6. Add the Interaction Scores for each System Choice's interaction with the set of System Choices to arrive at the total interaction score for each.
7. Divide the Interaction Score by the Total Variance and subtract it from one to normalize negative Interaction Scores. Take the reciprocal of this to arrive at the Interaction Factor.
8. Multiply the weighted performance score by the Interaction Factor for each System Choice to arrive at the adjusted Performance Score for each characteristic.
9. The Whole House Score is the sum of adjusted Performance Scores.

The resulting number is only useful as a comparison to another set of System Choices. To make the whole house score more meaningful, a perfect score for the whole house is generated by scoring all performance factors as a value of five, and all interactions as a value of three. The system weighting and user weighting values are applied to arrive at a theoretical perfect score.

Dividing the Whole House Score by the theoretical perfect score generates a percentage reflecting how closely this particular configuration of processes, components and subsystems is to the ideal.

Part IV: Sample Calculations with the Whole House Calculator

The initial application of the calculator compared two house alternatives. The first is a 'typical' house built by a production builder. The second house is also built by a production builder but uses a 'systems' approach.

The actual specifications of the houses were used to determine the Systems Choices. For purposes of demonstrating the calculator function, the research team developed performance and interaction scores for the System Choices for the sample houses to populate the two sets of databases. The performance and interactions scores are for example use only and do not reflect any absolute values. In developing these sample scores, the research team assumed the following:

- IRC Code Compliance;
- Mid-Atlantic regional location for decay, weathering, termite infestation probabilities;
- Inland wind exposure;
- Seismic design category "A";
- Radon Zone 1; and
- Climate Zone 10.

User Values

For both the test houses, the User Values for the homebuyer were used in the calculator. The following values were used for purposes of demonstrating the calculator function.

o Comfort	15
o Healthy	10
o Dry	20
o Sturdy	20
o Safe	15
o Flexible	10
o Efficient	10

Subsystem Weighting

Based on the assumptions above, the following subsystem weighting factors were used.

Subsystems	Weighting factor
• Process & production design	5
• Foundation	15
• Superstructure	25
• Envelope	15
• Interior partitions & finishes	2
• Millwork	3
• Utility distribution	7
• Electrical power & light	10
• Sewer & water	5
• Thermal systems	13

Initial Application of the Calculator, Example 1, Typical House

The first example has 93 characteristics describing a typical production house.

Process and Production Design were described with 23 System Choices:

1. Purchased Design, no site design.
2. Proscriptively described structural system.
3. Proscriptively described thermal system.
4. Proscriptively described water, sewer, and gas.
5. Proscriptively described electrical system.
6. <1' overhangs.
7. Full basement.
8. Vented attic.
9. Grading slopes away from foundation.
10. No landscape design.
11. Minimal exterior corners.
12. Minimal envelope penetrations.
13. Traditional stick frame.
14. All subcontracted, self supervision.
15. No quality check of personnel training.
16. No quality check of completed work.
17. No quality check of performance.
18. No quality check at project end.
19. No formal safety training at personnel start.
20. No daily safety briefings.
21. No daily safety inspections for rigging or trenches.
22. No material/tooling design for safety.
23. Safety a personal decision.

The foundation system was described with seven System Choices:

1. Site cast concrete footing.
2. Masonry foundation wall.
3. Wire mesh reinforced slab on grade.
4. Fiberglass board insulation.
5. Trowel on asphaltic water management layer.
6. Four mil poly sheet below slab on grade.
7. Drain tile at footing - excavated clay backfill.

The superstructure system was described with four System Choices:

1. Dimension lumber framed on site.
2. Dimension lumber wall framing system.
3. Shear panels at corners only.
4. Dimension lumber roof framing.

The envelope system was described with sixteen System Choices:

1. Vinyl siding.
2. Face sealed wall.
3. Housewrap air barrier.
4. Unfaced batt insulation in stud cavity.
5. Poly sheet vapor barrier on inside of wall.
6. Tape sealed nail flange wall opening flashing.
7. Asphalt shingle roof membrane.
8. Bituthene sheet ice guard.
9. Building paper secondary membrane.
10. Blown fiberglass roof insulation.
11. No cathedral ceilings.
12. Roof vent eave to ridge no chutes.
13. Roof flashing site fabricated metal.
14. Floor insulation glass batts.
15. Floor water vapor management – none.
16. Floor ventilation – none.

The interior finish and partition system was described with nine System Choices:

1. Site framed wood framing.
2. Drywall substrate.
3. Vinyl wall covering finish at exterior wall.
4. Vinyl wall covering finish at interior wall.
5. Particle board subfloor.
6. Pad and carpet floor finish.
7. Vinyl sheet goods floor finish.
8. Drywall ceiling substrate.
9. One high build primer finish coat ceiling finish.

The millwork system was described with three System Choices:

1. Milled wood interior trim.
2. Prefabricated engineered wood cabinets.
3. Plastic laminate countertops.

The utility distribution strategy was described with three System Choices:

1. Bundled based on schedule systems integration.
2. Site fabricated trunks and feeders.
3. Water piping in conditioned and unconditioned spaces.

The electric power and light system was described with five System Choices:

1. Wiring is romex.
2. Each system is separately wired.
3. Electrical system is on-grid.
4. Lighting system designed by installer.
5. Lighting system is incandescent.

The sewer and water system was described with seven System Choices:

1. Water piping is copper.
2. Only hot water piping is insulated.
3. Sewer piping is within partitions.
4. Water supplied by municipal system.
5. No water treatment system in house.
6. No cistern.
7. Municipal sewer disposal.

The thermal systems were described with fifteen System Choices:

1. Plumber installed gas appliances and vents.
2. No third party vent testing.
3. Owner provides appliances, vendors install.
4. Ductwork in unconditioned locations.
5. Site formed ductboard trunks.
6. Flexduct feeders.
7. Gas furnace.
8. Air distribution.
9. Stand alone hot water heater and storage.
10. Perimeter diffuser locations.
11. Low velocity air supply.
12. Point diffusers.
13. Central ducted return.
14. Exhaust driven makeup air.
15. Gas fireplace on exterior wall.

Calculator Example 1 Typical House Score
The resulting whole house score was 5,266. This represents 15.81% of the best possible score (33,302) for a house comprising 93 characteristics.

Example 2 Systems Approach House

The second example is formulated to compare a house produced with a systems approach with the previous example of a typical production house.

A set of processes, materials, components and systems were chosen to describe an alternative to the typical house. This set reflects a systems approach to the production house, similar to that discussed in Part I of this report.

This house had 88 characteristics overall. Process and Production Design were described with twenty-one System Choices:

1. Architect and Engineer.
2. Production Design, Custom Siting.
3. Fully Engineered Structural System.
4. Fully Engineered Mechanical System.
5. Fully Engineered Water, Sewer and Gas System.
6. Fully Engineered Electric Power and Light System.
7. Overhangs > 1 foot.
8. Ventilated Attic.
9. Grading Designed to slope away from foundation.
10. Landscape designed integration.
11. Minimum Exterior corners.
12. Minimal Envelope penetrations < 16.
13. SIPs Panel construction method.
14. In-house superintendent, in-house shell crew, minimal subs.
15. Quality check of personnel training.
16. Quality check of work as increments are completed.
17. Quality check of performance of the work.
18. Safety training for personnel at project start.
19. Daily safety briefings.
20. Daily safety inspections for rigging, trenching, temp structures.
21. Tooling and materials designed for safety.

The foundation system was described with nine System Choices:

1. Crushed rock footing.
2. Precast concrete foundation.
3. Wire mesh reinforcing for slab on grade.
4. Extruded polystyrene. foundation insulation.
5. Sheet applied bituthene foundation waterproofing.
6. Six mil poly sheet horizontal moisture control membrane.
7. Drain tile at footing.
8. Drain board.
9. Free draining backfill.

The Superstructure system was described with four System Choices:
1. Prefabricated trusses and floor panels, factory assembled.
2. SIPs panel exterior walls.
3. Fully sheathed in shear panels.
4. Prefabricated wood truss roof framing.

The envelope system was described with fifteen System Choices:
1. Masonry veneer siding
2. Water managed wall (rainscreen).
3. Asphalt impregnated building paper wall air barrier.
4. No additional wall insulation, sips panel only.
5. No additional wall vapor barrier, sips panel only.
6. Prefabricated plastic window flashing.
7. Asphalt shingle roof.
8. Bituthene sheet ice guard.
9. Building paper secondary membrane.
10. Glass batt attic insulation.
11. Roof ventilation, eave to ridge, preformed chutes.
12. Prefabricated metal roof flashing.
13. Glass batt floor insulation.
14. Building paper floor vapor barrier.
15. No floor ventilation, basement.

The interior partitions and framing system was described with eight System Choices:
1. Prefabricated light gauge steel partitions.
2. Drywall wall finish substrate.
3. One latex primer, two finish latex paint at exterior wall.
4. One latex primer, two finish latex paint at interior wall.
5. OSB subfloor.
6. Pad and carpet floor finish.
7. Drywall ceiling.
8. One high build primer/finish paint coat at ceiling.

The millwork system was described with three System Choices:
1. Stone countertops.
2. Milled wood interior trim.
3. Prefabricated milled wood cabinets.

The utility installation and distribution strategy was described with eight System Choices:
1. Plumber installed gas venting.
2. Third party tested gas venting.
3. Appliances by builder.
4. Unbundled systems integration strategy.
5. Prefabricated trunks and feeder utility distribution strategy.
6. Ductwork in conditioned spaces.
7. Prefabricated ductboard ducts.
8. Water piping all in conditioned spaces.

The electric power and light system was described with five System Choices:

1. Electrical wiring romex.
2. Communication wiring cat 5/6.
3. On grid power.
4. Lighting designed by lighting engineer.
5. Lighting compact fluorescent.

The sewer and water system was described with eight System Choices:

1. Water piping copper.
2. All water piping insulated.
3. Sewer piping in partitions.
4. Municipal water.
5. Filtered.
6. Softened.
7. No storage of water.
8. Municipal disposal of waste.

Thermal systems were described with eight System Choices:

1. Gas hot air furnace.
2. Air distribution system.
3. Integrated hot water and furnace.
4. Core diffuser locations.
5. Low velocity air.
6. Point diffusers.
7. Individual returns ducted from each space.
8. Air to air heat exchange ventilation.

Calculator Example 2 Systems Approach House Score
The same user values were applied. The resulting whole house score was 7,420. This represents 26.8% of a best possible score (28,025) for a house comprising 88 characteristics.

These numerical scores would be augmented in a summary report on the house by noting any potentially problematic interactions between the system characteristics. An example of these “yellow flags” follows:

”Combining a gravity vented crawlspace, without a vapor barrier over the soil, when using the crawl space to route metal air conditioning ducts may contribute to high levels of moisture in and on wood surfaces of the floor and wall structure. This can contribute to favorable conditions for the growth of mold, mildew, decay fungi and insect infestations that can seriously compromise the health and safety of the occupants of this house in this climate zone.”

Part V Needs, Opportunities and Conclusions

The absence of consensus data on process and systems component performance and interaction data is a significant impediment to broadly implementing the whole house calculator or advancing the whole house approach to design and construction. It is suggested that future work in developing the whole house calculator be focused on establishing performance and interaction scores for each characteristic of process and system. The "expert panel" approach in use by the U.S. Department of Energy appears to be the most appropriate method available to expedite development of this data.

These expert panels should represent:

- Appropriate materials, component, systems producers;
- Designers and engineers of housing;
- National and Regional builders;
- Third-party building scientists;
- Regional building officials;
- Insurance industry officials; and
- FEMA officials familiar with regional disaster performance.

Expert subsystem panels should be convened on:

- Whole-house systems interactions;
- Process and production design;
- Foundation;
- Superstructure;
- Envelope;
- Interior finishes and materials; and
- Utility systems.

To support integration across each subsystem panel discussion, each panel discussion would include a representative from each subsystem expertise group.

Each subsystem expertise group meeting would be tasked with arriving at consensus scores for:

- Weighting factors for each of the subsystems;
- The performance of alternative methods of design and construction;
- The interactions between the systems characteristics.

Two alternatives to this expert consensus approach seem possible. The first would be to establish standard tests for performance and interaction with other materials, components and systems. This data could be furnished by the innovator as part of the material certification process required by building codes. This would assure a stream of data into the calculator in future years. The second alternative, which may be necessary for existing materials, components and systems would commission research projects to definitively establish a performance ranking of each alternative characteristic for each subsystem, as well as projects to definitively establish the values for performance enhancement or degradation of subsystems and components during multiple levels of interaction. The number of individual tests needed in this approach might exceed fifteen million.

Further development on the calculator itself is needed to study the effect of the interaction score on the performance score. It may be necessary to consider alternative scales for scoring interactions, and alternative methods of factoring these scores to appropriately reflect the impact of the interactions on performance.

Once filled with data, whole house calculator is designed to be used by designers, buyers or designer/builders interested in comparing alternative combinations of processes, systems, components or materials in the context of the house as a whole, and to compare one house to another.

A designer or builder may use the calculator to better understand the implications of a process, product, component, system or material on the house as a whole. Additional information on the location of the project will be used to identify the climate zone, seismic zone, and wind exposure zone from a lookup database.

Data from the builder or designer's CAD model would be extracted to populate the database with an outline specification of baseline materials, components and systems. A menu of outline specification components could be offered for the builder or designer to choose the materials, components or systems in the house, or preconfigured standard outline specifications could be offered for purposes of comparing the effect of an innovation or change on the whole house.

The outline specification configures lookup functions in the database to extract the performance and interaction data for the material, component or system from the database.

A prospective buyer might fill out one of these input forms as an online questionnaire. The buyer's interest in specific aspects of the performance of the house would be subsequently translated into a distribution of points comprising a mathematical description that reflects the buyer's performance expectations.

Additional information on desired locations, number of bedrooms, amenities and styles, multiple listings of houses would be presented. Each house listing would carry with it the characteristics of the processes, products, components and materials used to construct it. This listing would effectively configure the lookup functions to extract the performance and interaction scores for each characteristic.

The prospective buyer's point value distribution modifies the performance scores, as does the interaction scores to produce a total score for the house in question.

The comparison of scores across the multiple houses listed would allow the owner to know how closely matched a particular house is to their expectations. The score would be broken down into the categories of outcomes, so the buyer might have a better idea where additional investment might improve the fit of the house to their family.

The Whole House Calculator as a tool to advance the Whole House Approach:

In considering how the whole house calculator could be used to advance the whole house approach in the homebuilding industry, two directions seem possible. First, the calculator as a what-if tool used during the design, and production planning stages to assess the impact of alternative Systems Choices individually or in bundles in an iterative process of trial and assessment. Second, the calculator could be used as a strategic planning tool for design, specification and production planning. This latter approach might be conceptualized as a targeted unraveling of the expertise embedded in the calculator itself.

The unraveling might initially proceed by the user identifying the location of the project and user space needs. This information would delimit the database and select a set of System Choices for the location-sensitive data, climate, seismic, wind and radon exposure, embedded in the calculator. Each System Choice could be modified by the user as desired. Upon each change to a System Choice, the database would update and revise the displayed System Choices. If the user attempts to choose two conflicting Systems Choices, a caution note would be displayed indicating the risk related to the choice. Thus the calculator could be used as an online advisor. Homebuilders might use it to learn the value or risks associated with certain combinations of Systems Choices while prospective homeowner might use it to understand the components critical to meeting their needs in a specific location.

Glossary of Terms

Building Information Model (BIM): A design and production approach to Computer Aided Design that treats the drawings as a database containing information about the graphic

Computer Aided Design (CAD): An automated system for the design, drafting and display of graphically oriented information.

Expanded Polystyrene (EPS): Preformed-molded boards of expanded polystyrene beads used to enhance the thermal resistance of building envelopes.

Extruded Polystyrene (XPS): Preformed-extruded boards of closed cell polystyrene foam used to enhance the thermal resistance of building envelopes.

Heating, Ventilating, Air Conditioning (HVAC): The systems and constituent components used to control the temperature, humidity and air exchange in an indoor air environment.

Insulating Concrete Formwork (ICF): A concrete form system that combines the formwork, form ties in an insulated shell that is left in place upon completion of reinforcing and concrete placing for walls.

Just-In-Time (JIT): A manufacturing approach, which seeks to eliminate waste by providing the right part, at the right place and at the right time.

Optimum Value Engineering (OVE): A set of techniques developed to optimize the amount of lumber in a house frame, reduce labor costs and improve energy performance.

Oriented Strand Board (OSB): Directionally formed particleboard comprising cross-bonded plies. Substitute for plywood in building.

Parametric CAD: Capability of some CAD systems to keep a directed set of relationship so that changes can be propagated to following constructions. In some cases theses relationship will correspond to the design intend and some mechanical logic of the design.

Performance: The measure of the behavior of a physical element or system in an environment.

Polyisocyanurate Insulation Board (Polyiso): Insulation produced principally by the polymerization of polymeric polyisocyanates, usually in the presence of polyhydroxyl compounds with the addition of cell stabilizers, blowing agents, and appropriate catalyst to produce a polyisocyanurate chemical structure used to enhance the thermal resistance of building envelopes.

Radon: A naturally occurring colorless, odorless, inert radioactive gas produced from the natural decay of uranium that is found in trace amounts in nearly all soils. In some parts of the country, this gas can accumulate in basements in sufficient concentrations to cause health problems. The EPA has established guidelines for responding to radon gas concentrations of greater than 4.0 picocuries/liter of air.

Smart Agent: A small, user-customized, task-oriented software application often used to perform search tasks on large networks.

System: A group of independent but interrelated elements comprising a unified whole.

Systems Approach: A systematic process of problem solving that defines problems and opportunities in a systems context. A logical process for effectively and efficiently planning which considers all elements of a system.

Tankless Water Heater: Tankless water heaters provide hot water when needed without storage, thereby reducing or eliminating standby losses incurred when keeping a reservoir tank of water heated during times when the house is not occupied.

Tradition: A custom: a specific practice of long standing. An inherited pattern of thought or action.

Whole House Calculator: A method for numerically evaluating the speculative performance of a house based on the numerical performance of the processes, materials, components and systems individually and collectively.

References:

Martel, Gary and Lackey, Robert, A Computerized Method for Abstracting and Evaluating Environmental Impact Statements, Bulletin 105 Virginia Water Resources Research Center, Virginia Tech, December 1997.

Newport Partners LLC, Whole-House and Building Process Redesign, PATH Roadmap, HUD Partnership for Advancing Technology in Housing, 2003 update.

O’Brien et. al., VA Tech Center for Housing Research, Industrializing the residential Construction Site, Phase III Production Systems, HUD Partnership for Advancing Technology in Housing, June 2002.

Appendix 1: House Part Count

House parts list

1 excavation
2 footing
3 slab isolator
4 slab cushion
5 slab vapor barrier
6 slab reinforcing
7 slab drain
8 slab
9 sewer straight pipe
10 elbow
11 tee
12 foundation
13 foundation reinforcing
14 foundation insulation
15 foundation waterproofing
16 foundation drain
17 foundation backfill
18 foundation anchor bolts
19 treated mud plate
20 sill seal
21 rim joists
22 joists
23 joist bridging
24 subfloor
25 finished floor
26 wall stud/plate
27 wall insulation
28 wall vapor barrier
29 wall sheathing
30 wall moisture barrier
31 wall siding
32 window
33 window flashing
34 window trim
35 door
36 door flashing
37 door trim
38 exterior door hardware
39 interior door hardware
40 closet door hardware
41 wall base trim
42 wall finish substrate
43 wall finish
44 electrical receptacle box
45 electrical conductor
46 electrical receptacle
47 electrical receptacle cover
48 electrical switch box
49 electrical switch
50 electrical switch cover plate
51 ceiling vapor barrier
52 ceiling substrate
53 ceiling finish
54 ceiling lighting box
55 ceiling lighting fixture
56 ceiling fan box
57 ceiling fan
58 roof trusses
59 roof truss bracing
60 roof sheathing
61 roof insulation
62 roof moisture barrier
63 roof finish
64 ice dam underlay
65 edge flashing
66 valley flashing
67 step flashing
68 roof vent jack
69 roof attic vent
70 gable vent grille
71 ridge vent
72 eave vent
73 soffit
74 fascia
75 gutter
76 downspout
77 hose bib
78 wp outlet
79 gfi outlet
80 dimmer
81 circuit breakers
82 main panel
83 meter base
84 pressure reducer
85 water filter
86 water softener
87 water heater
88 furnace
89 cooling coil
90 duct mains
91 duct distribution
92 duct register floor
93 duct register ceiling
94 exhaust fan
95 ceiling heat bathroom
96 mirror
97 countertop bath
98 vanity cabinet
99 towel bars
100 soap dish
101 grab bars
102 shower enclosure
103 tub shower fixture
104 floor fitting tub shower drain
105 floor fitting toilet
106 toilet
107 lavatory
108 closet shelf
109 closet rod
110 closet door
111 smoke detector
112 countertop kitchen
113 cabinets kitchen
114 stove exhaust hood
115 stove exhaust cap
116 bath exhaust cap
117 fireplace flue
118 fireplace flue cap
119 fireplace
120 fireplace doors
121 washer
122 dryer
123 dryer exhaust
124 phone entrance
125 catv entrance
126 doorbell
127 exterior light
128 security light
129 deck material
130 framing fasteners

131 millwork fasteners
132 drywall fasteners
133 toilet acc anchor
134 siding fastener
135 roofing fastener
136 decking fastener
137 framing hangers
138 decking hangers
139 window fasteners
140 window sealant
141 siding sealant
142 bath sealant
143 slab sealant

Number of parts =	143
x 4 alternatives choices for each part =	572 part choice alternatives
Combination of part types total	
(572 x 572) =	327,184
x 6 climate zones =	1,963,104
x 6 seismic categories =	11,778,624
x 8 compass orientations =	94,228,992
x 6 alternative house designs =	567,337,056 combinations of the system.

Appendix 2 Process, Material, Component, System Choices:

2.1 Design & Engineering Credentials

- Architect & Engineer
- Architect Only
- Engineer Only
- Unlicensed Designer
- None

2.2 Design & Engineering Services

- Custom Design & Siting
- Production Design, Custom Siting
- Production Design, Production Siting
- Production Siting, Production Design with prepacked options
- Purchased Design, no siting

2.3 Specific System Design Applications

- Structural Systems
- Fully Engineered
- Designed integration
- Engineered by suppliers or installers
- Components proscriptively described
- Components traditionally described

2.4 Thermal Energy Systems

- Fully Engineered
- Designed integration
- Engineered by suppliers or installers
- Components proscriptively described
- Components traditionally described

2.5 Water, Sewer & Gas Systems

- Fully Engineered
- Designed integration
- Engineered by suppliers or installers
- Components proscriptively described
- Components traditionally described

2.6 Electric Power and Light

- Fully Engineered
- Designed integration
- Engineered by suppliers or installers
- Components proscriptively described
- Components traditionally described

2.7 House Design Characteristics

- Presence of overhangs>1 foot
- Presence of ventilated attic
- Grading designed to slope away from fdn
- Landscape design integration
- Minimal exterior corners <8
- Minimal envelope penetrations <16
- OVE framing

3.1 Product Design

- Construction Method (panel, stick)
- Traditional stick frame
- Panelized stick frame
- SIPS Panels
- Prefabricated Modular
- Masonry
- ICF

3.2 Construction Method (min/max subs)

- In-house superintendent, all external subs
- In-house superintendent, In-house shell crew, minimal subs
- All in-house personnel
- All subcontract - self supervision

3.3 Formal Quality System Design

- Quality check of personnel training
- Quality check of work as increments are completed
- Quality check of performance of the work
- Quality check at the end of the project

3.4 Formal Safety System Design

- Safety training for personnel at project start
- Daily safety briefings
- Daily safety inspections for rigging, treching temp structures
- Tooling and materials designed for safety (label, cg, edges, switches, falls)
- Safety a personnel decision

4.1 Subgrade Systems

- Footing
- Site cast concrete
- Crushed rock

4.2 Foundation

- Masonry
- Site cast conrete
- Precast concrete
- Insulated Concrete Formwork (ICF)
- All Weather Wood (AWW)

4.3 Slab on Grade

- Glass Strand reinforcing
- Wire mesh reinforcing
- Rebar reinforcing
- Post tension strand reinforcing

5.1 Insulation

- Expanded Polystyrene (EPS)
- Extruded Polystyrene (XPS)

- Fiberglass Board
- Fiberglass Batts
- Mineral fiber blockfill

5.2 Water Management Layer (Vertical)
- Brush-on cementitous
- Brush-on asphaltic
- Trowel-on asphltic
- Spray-on bitumen
- Sheet-applied bituthene

5.3 Water Management Layer (Horizontal)
- 4 mil poly sheet
- 6 mil poly sheet
- Sand and gravel cushion
- None

6.1 Superstructure Systems
- Floor Framing
- Dimension lumber - site framed
- Engineered lumber - site framed
- Prefrabricated trusses - site assembled
- Prefabricated trusses & floor panels - factory assembled
- Light gauge steel

6.2 Wall Framing
- Dimension lumber
- Engineered lumber
- Light gauge steel
- Prefabricated panels
- Structural Insulated Panels - SIPS
- Masonry
- Insulated Concrete Formwork - ICF

6.3 Shear Framing
- Shear panels at corners only
- Let-in "T" bracing
- Fully sheathed in structure panels
- Prefabricated shear panels (eg strongwall)
- Light gauge steel

6.4 Roof Framing
- Dimension lumber
- Engineered lumber
- Prefabricated wood trusses
- Prefrabricated light gauge steel trusses

7.1 Envelope Systems

Wall Exterior Finish
- Sawn wood siding
- Plywood siding
- Composition board siding
- Cement board siding
- Masonry veneer
- Vinyl siding
- Metal siding
- Acrylic-stucco, Exterior insulation and Finish System (EIFS)

7.2 Bulk Moisture Management
- Water managed wall (rainscreen)
- Face-sealed wall

7.3 Air Barrier
- Housewrap
- Perforated Housewrap
- Water managing housewrap
- Asphalt-impregnated building paper
- Kraft paper
- Sealed exterior gypsum sheating

7.4 Insulation
- Glass batt in stud cavity-unfaced
- Glass batt in stud cavity-foil faced
- Glass batt in stud cavity-paper faced
- Glass batt in stud cavity with extruded polystyrene board sheat
- Glass batt in stud cavity with foil faced polyiso board sheating
- Mineral fiber batt or fill
- Expanding foam in stud cavity

7.5 Water Vapor Management
- Poly sheet barrier
- Vapor-retarding latex paint
- Vinyl wall covering
- none

7.6 Opening Flashing
- Field applied bituthene sheet
- Field fabricated metal
- Prefabricated metal
- Prefabricated plastic
- Tape-sealed nailing flange

8.1 Roof
- Primary membrane
- Asphalt shingles
- Wood shingle
- Prefinished metal
- Clay or cement tile

8.2 Ice Guard
- Bituthene sheet
- Hot-mopped roofing felt
- Building paper
- None

8.3 Secondary Membrane
- Bituthene sheet
- Hot-mopped roofing felt
- Building paper
- None

8.4 Insulation - Attic
- Blown fiberglass
- Blown mineral fiber
- Blown cellulose
- Glass batts
- Mineral fiber batts

8.5 Insulation - Cathedral

- EPS SIP
- XPS SIP
- Polyiso SIP
- Glass batts
- Mineral fiber batts

8.6 Ventilation - Attic
- Eave to ridge - no chutes
- Eave to ridge - preformed chutes
- Power vents - temperature controlled

8.7 Flashing
- Prefabricated metal
- Site - formed - membrane
- Site fabricated metal
- Preformed plastic

9.1 Floor
- Insulation
- Glass batts
- Mineral fiber batts
- Blown fiberglass
- Blown mineral fiber
- None

9.2 Water Vapor Management
- Poly sheet
- Building paper
- None

9.3 Ventilation
- Gravity vent
- Power vent
- None

Interior Partitions and Finishes
10.1 Partition Framing
- Site framed wood
- Prefabricated wood
- Site framed light gauge steel
- Prefabricated light gauge steel
- Masonry

10.2 Wall Finish Substrate
- Plaster
- Drywall
- Reduced-cellulose drywall
- Drywall over engineered wood (SIPS, OSB, plywood)
- Masonry
- ICF

10.3 Interior finish at exterior wall
- 1 latex primer + 1 finish latx
- 1 latex primer + 2 finish latex
- Vinyl wall covering
- Wood veneer paneling
- Ceramic tile
- None

10.4 Wall finishes (int. wall)
- 1 latex primer + 1 finish latex
- 1 latex primer + 2 finish latex
- Vinyl wall covering
- Wood veneer paneling
- Ceramic tile
- None

11.1 Subfloor
- Particle board
- OSB
- Plywood
- Cement board
- Concrete

11.2 Floor finishes
- Pad and carpet
- Direct-glued carpet
- Vinyl sheet goods
- Vinyl tile
- Ceramic tile
- Hardwood
- Hardwood-veneer

12.1 Ceiling substrates
- Plaster
- Drywall
- Reduced-cellulose drywall
- None

12.2 Ceiling finishes
- 1 latex primer + 1 finish latex
- 1 high-build primer / finish coat
- Lay-in tile
- None

13.1 Countertops
- Plastic laminate
- Stone
- Cultured stone
- Soild cast arylic-plastic
- Ceramic tile
- Metal

13.2 Millwork & Appliances
- Interior trim
- Milled wood
- Milled or formed wood composite
- PVC
- Other plastic

13.3 Cabinetry
- Prefabricated - milled wood
- Prefabricated - engineered wood
- Custom fabricated - milled wood
- Custom fabricated - engineered wood

14.1 Gas Appliance Venting
- Plumber-installed
- Builder-installed
- Owner-installed
- Third-party-tested

14.2 Appliance Subcontract Method
- By builder
- By owner

15.1 Utility Distribution
- Integration Strategies
- Bundled-weaved together based on schedule

- Unbundled-each subsystem has designed place
- Hybrid-system trunks in designed places, distribution woven

15.2 Production Strategies
- Site fabricated trunks and feeders
- Prefabricated trunks and feeders
- Hybrid, prefabricated trunks, site fabricated distribution

15.3 Ductwork Location
- In unconditioned spaces
- In conditioned spaces

15.4 Ductwork Material
- Site formed metal
- Site formed ductboard
- Flexduct
- Prefabricated metal
- Prefabricated ductboard

16.1 Water Piping Location
- All in conditioned spaces
- In conditioned and unconditioned spaces

16.2 Water Piping Material
- Copper
- Polyisobutylene
- PVC
- CPVC
- HPBE

16.3 Water Piping Insulation Strategy
- All insulated
- Hot water only insulated

17.1 Sewer Piping Location
- Within partitions
- Directly to subgrade

17.2 Sewer Piping Material
- PVC
- Iron

18.1 Electrical wiring strat (conduit, romex)
- Conduit
- Romex
- Wiring harnes

18.2 Communication wiring strat (cat5, sep)
- Category 5/6
- Separate wiring for each system

18.3 Electric Power & Light
- Generation Types
- On grid
- Self - PV generation
- Self - wind generation
- Self - gas or propane generator
- Hybrid on-grid and self-generation

18.4 Lighting Design Types
- Designed by lighting engineer
- Designed by electrical engineer
- Designed by architect
- Designed by supplier
- Designed by installer

18.5 Lighting Types
- Incadescent
- Compact fluorescent
- Low Voltage

19.1 Water & Sewer
- Source Strategies
- Municipal
- Private well
- Purchased service

19.2 Treatment Strategies
- None
- Filtered
- Softened

19.3 Storage Strategies
- None
- Cistern

19.4 Disposal Strategies
- Municipal
- Septic system
- Storage tank

Thermal Systems
20.1 Source Strategies
- Gas / oil / electric boiler or water heater
- Gas / oil / electric hot air furnace
- Ground coupled electric heat pump
- Air source electric heat pump

20.2 Distribution medium Strategies (water, air, radiant)
- Radiant slab water
- Hot water radiator
- Air

20.3 Domestic Hot water Integration Strategies (dhw & hvac)

- Integrated hot water and furnace
- Stand alone hot water heat and storage
- Tankless hot water source heaters
- Solar hot water heat and storage

21.1 Supply Strategies (loc, vel, diff, char)

- Perimeter diffuser locations
- Core diffuser locations

21.2 Air Velocity

- Low velocity
- High velocity
- Ultra velocity

21.3 Diffuser Characteristics

- Pressure-reducing
- Point
- Linear

21.4 Return Strategies

- Individual returns for each ducted space
- Central ducted return
- Ducted return for each floor served
- Panned joist return duct

21.5 Vent Strategies

- Continuous supply ventilation
- Exhaust-driven makeup air
- Air to Air heat exchange
- Heat recovery exchange

21.6 Fireplace Strategies

- Masonry on exterior wall
- Masonry on interior wall
- Metal on exterior wall
- Metal on interior wall

Appendix 3: Operating the Calculator

The calculator is included with this report as two MS Excel files titled "Sample Calculation - Typical House.xls" and "Sample Calculation - Systems Approach House.xls". These files are example applications of the whole house calculator and have been populated with performance and interaction data for demonstration purposes only. Similarly, no user-friendly interface has been developed at this point. It is hoped that future whole house projects would be focused on developing interfaces for both prospective homebuyers and professional builders.

The following pertains specifically to the file titled "Sample Calculation - Systems Approach House.xls".

The files open to an Excel sheet with the title "User input & perf score" on the tab at the lower left corner of the window. This is the place where the user distributes up to 100 points between the User Value topics:

- Comfort (temperature, load responsiveness, humidity, air velocity)
- Healthy (VOC's, dust, particulates, fibers, air quality)
- Dry (bulk moisture management, no mildew)
- Sturdy (no visible deformation, no envelope breach in 100 year events, no damage from 50 year events)
- Safe, (fire detection, suppression, egress, fall hazards)
- Flexible, (change during construction, aging, multiple households, do-it yourself)
- Efficient

The Excel file links these user weighting factors to performance scores. The performance scores are also modified by the subsystem weighting factors visible by scrolling to cell "M1". We anticipate these subsystem weighting factors will be determined in future Whole House projects focused on obtaining performance, interaction, and subsystem weighting factors through expert panels in a consensus process.

Scrolling to cell "A21" shows a calculated value linked to the user value weights. Changing the user value weights at cell D55-61 will change the values in cells "A22" through "A44". These cells, "A22" through "A44", become multipliers for the system raw performance scores listed directly below the headings in row 21, as do the subsystem weighting factors in cells P5 through P11. Once multiplied by the raw performance scores, the modified values are summed in row 45 to arrive at an adjusted performance score for the house composition characteristics.

These adjusted performance scores are linked to the sheet tab named "interaction & tot score", in the lower left corner of the window.

Clicking on this tab takes you to the sheet where the interactions between the house composition characteristics are scored. The interaction scores for each characteristic are totaled in column "CN", factored in column "CO", and applied to the adjusted performance score to arrive at the adjusted performance factor in column "CR".

The whole house score is the sum of these adjusted performance factors in column "CR" shown as a total in cell "CR107". A separate sheet calculates the best possible score for which is shown in cell "CV110" and described in part three of this report. Dividing the whole house score by the best possible score generates the percentage of the best possible score for the house.