A STRATEGY TO PROVIDE COMPUTATIONAL SUPPORT FOR THE SELECTION OF ENERGY SAVING BUILDING COMPONENTS

P. de Wilde[1], G. Augenbroe[2] and M. van der Voorden[1]
1. Delft University of Technology, Faculty of Architecture, Building Physics Group
Delft, 2600GA - The Netherlands
2. Georgia Institute of Technology, College of Architecture, Doctoral Program
Atlanta, GA 30332-0155 - U.S.A.

ABSTRACT

This paper describes a strategy to provide computational support for the selection of energy saving building components. The strategy rationalizes a small but significant part of the building design process by providing a clear procedure for a decision making process in which the use of computational tools is embedded; it is based on systems engineering, engineering design and decision theory. Consequences for the embedded computational tools of using this strategy for the selection of energy saving building components are discussed; a prototype providing process support is presented.

KEYWORDS

building design, building simulation, process integration, systems engineering, engineering design, decision theory, computational tools, prototype

1. INTRODUCTION

In contemporary architecture an increasing emphasis on performance aspects like energy consumption and comfort can be observed. The deployment of novel design features like solar walls, advanced glazing systems, sunspaces and photovoltaic arrays is on the rise. Generally the efficiency of such energy saving building components cannot be studied in isolation. They are dependent on building characteristics whereas interaction between components can have a substantial effect on the efficiency of each individual component. The impact of climate conditions and occupant behavior add to the complexity and make it almost impossible to predict performance without use of computational tools.

The building physics profession has a large number of energy-related computational tools at its disposal; these tools range from simple to sophisticated computer programs, and range from tools that consider one aspect only to tools that take a more integral view. These tools allow comparison of various design options under identical conditions.

Earlier research at Delft University of Technology dealt with the integration of energy saving building components in real-life building design scenarios as well as the use of computational tools in these scenarios. The results indicate that most energy saving building components are selected without proper underpinning, and that computational tools only play a limited role in the selection of energy saving components, mainly due to the design decision process currently in use. The crucial design phase for the selection of energy saving building components appears to be the phase of conceptual design. The conclusion is that future developments in the field of ‘design tools’ should include the development of procedures (‘process templates’) for specific parts of the building design process in which the use of appropriate computational tools (both existing and future tools) can be embedded (de Wilde et al. 1999, de Wilde et al. 2001).

2. GOAL

Goal of the research presented in this paper is the development of a strategy to support rational decisions with respect to the integration of energy saving components in building design. The strategy must address the afore-mentioned issues; use of computational tools will be embedded. The strategy should especially be applicable during the conceptual design phase; however, it should not interfere with the rest of the building design process (which in parts can be highly intuitive and unpredictable).

3. APPROACH

The strategy is based on the concepts of ‘systems engineering’ (Hazelrigg 1996, Blanchard and Fabrycky 1998), augmented with theories from ‘engineering design’ (Cross 1993) and ‘decision theory’ (Keeney and Raiffa 1993). The underlying fundamentals from these disciplines will be briefly discussed in the first part of the paper.

The second part of the paper deals with the application of these concepts to that part of the building design process that deals with the selection of energy saving building components (with emphasis on the conceptual design phase). Weaknesses in the current selection process will be pointed out whereas the framework that supports the strategy presented in this paper will be addressed.

The third part of the paper examines the consequences of the rational decision framework for required computational tools in more detail. Specific needs for computational support are defined and the suitability of currently existing computational tools to fulfill these needs is discussed. Combination of the framework and existing tools results in the strategy that is the goal of this research project.

Finally the development of the prototype 'RPSE' (Rational Procedure for the Selection of Energy saving building components) is presented to demonstrate the feasibility of an operational design decision support system based on this strategy.

4. UNDERLYING FUNDAMENTALS

4.1 Systems Engineering

Systems engineering can be defined as the application of scientific principles to the design, development, implementation and control of systems, where a system is a set of interrelated components working together towards some common objective or purpose. System engineering can be applied to many disciplines; however, though there is general agreement on the principles and objectives of system engineering, each application will strongly depend on this discipline and the background and experiences of the participants, as well on the complexity of the system (Blanchard and Fabrycky 1998, INCOSE). The applicability of systems engineering to building design has been demonstrated in the context of cost control (Merrit and Ambrose 1990).

Systems engineering addresses all major life-cycle processes of systems: systems design, development, production/construction, distribution, operation, maintenance/support, phase-out and disposal; in this paper the emphasis within systems engineering will be on (conceptual) systems design.

According to the systems engineering approach the design process encompasses four distinct activities: the analysis of objectives and constraints; the identification of all design options that are to be considered; the development of expectations on outcomes for each option; and the use of values to select the option that has the range of outcomes and associated probabilities that are most desired.

The first activity consists of determination of the objectives that the design team wants to achieve and determination of limiting factors (constraints). For each objective and/or constraint attributes must be identified that describe the extent to which these objectives are being achieved or constraints are being met. Attributes are also known as (technical) performance measures or more generally as performance indicators; in this paper the last term will be used. It is important that the list of performance indicators is complete (adequately covers the objective), operational (meaningful) and non-redundant (preventing double counting of achievements). Additionally the set of performance indicators should help to decompose the objective(s) into manageable parts, while at the same time being of minimum size.

Limiting values for specific performance indicators are called goals or requirements. Goals are values that the design team strives to achieve; requirements are values that a design must meet in order to be acceptable. Both goals and requirements are either fulfilled or not.

Note that in most design projects objectives, constraints, attributes, requirements and goals are not present from the outset. Normally the client provides only general needs and wishes that must be translated into objectives, requirements and goals. Constraints are frequently dependent of actual design proposals and hence need to be defined during the course of the design process.

The second activity is identification of all design options that are to be considered; in systems engineering the set of all these options is named the 'option space'. Definition of an option space requires design synthesis or the definition of system configurations, and parameterization or identification of the parameters and their permissible ranges.

An option space can be constructed by eliminating possibilities from the set of all possible constructs, or by starting from one construct and adding options for consideration. Adding options is an appropriate approach when using existing components to design new systems (Hazelrigg 1996).

The third activity is the development of expectations on outcomes for each design option. Outcomes are the achievements of the individual options for objectives and constraints, described using the performance indicators. Theoretically the outcomes should be expressed in terms of predicted achievements and associated probability of occurrence, because of uncertainty in the design itself, the conditions in which the design will perform, and the prediction method. Although this is not always feasible, recent progress in assessing uncertainties in building performance assessments is reported in (de Wit and Augenbroe 2001). The set of outcomes is named 'outcome space'.

The fourth and final activity is selection of the design option that has the range of outcomes (and associated probabilities) that are most desired. This involves determination of the values of all design options. A value indicates the attractiveness of each design option in relation to the objectives and constraints. If this value is purely based on objectified performance measures, it is called 'utility'. If overlaid by the

preferences or 'value system' of the observer it is more appropriate to call it 'quality'.
Based on the obtained values one design option must be chosen. This involves mostly a decision problem with several objectives and/or constraints, determination of preferences and value trade-off. It can be advisable to use a formal decision method (weighting or utility function) that supports the decision maker by dividing one complex choice problem into several simpler choice problems (Keeney and Raiffa 1993, Roozenburg and Eekels 1991).

The four activities will reoccur many times during one design process. New objectives and constraints will emerge, new options will be added and evaluated, and the design will develop by a chain of design decisions.

4.2 Engineering Design

System engineering as a whole provides a too general approach. For application to the technical design of buildings, specific methods need to be selected and tailored.

One engineering design method that will be used is the 'objective tree method' which shows the design objectives in a diagrammatic form; it clarifies the relationships between objectives as well as the hierarchy of objectives and sub-objectives. The approach for developing an objective tree consists of first identifying 'areas of concern'; within these areas of concern, objectives can be identified, and if needed lower-level objectives can be identified within the objectives.

Principles from engineering design will also be used to support the step of design synthesis. This step consists of the definition of system configurations or, in other words, generation of alternatives; it is the creative part of the procedure. However, engineering design theory states that creativity often consists of reordering or recombination of existing elements into a wide range of variants, often resulting in novel solutions. The use of existing elements has the additional advantage that it allows the design team to avoid some detailed design work. It also eliminates uncertainty from an area of the overall design, as the specification of the element in question is known. However, the use of existing elements leaves aside the creation of novel elements. A method that helps to generate alternative design solutions from known elements is the morphological chart method; it consists of listing essential functions of the design under development, listing means (the existing elements) by which these functions might be achieved, and combining these means to define the total search space (the set of all possible option spaces) for this design project (Cross 1993).

4.3 Decision Theory

Decision theory is concerned with making rational choices between alternatives by applying (mathematical) methods. Within decision theory a distinction is made between single- and multiple-attribute decision problems, depending on the number of descriptors (attributes) that are needed to specify the consequences of a decision. Also a distiction is made between problems under certainty or uncertainty. For problems under certainty the consequence(s) of a decision are known; for problems under uncertainty there is a range of possible consequences. Making decisions under uncertainty involves taking (or limiting) risks.
Decision methods that provide a preference order are named ordinal methods; methods that provide a preference order as well as a measure of the strength of these preferences are named cardinal methods (Keeney and Raiffa 1993).

The most widely used method suitable for multiple-attribute decisions under certainty consists of an additive utility function and is described by:

$$U(A_i) = \sum_{j=1}^{m} \lambda_i e_{ij}$$

where:

$U(A_i)$ = utility of alternative A_i with regard to all criteria $C_1, \dots, C_m$

A_i = alternative i, i = 1, …, n

C_j = criterion j, j = 1, …, m

λ_j = weighting factor of criterion C_j, representing the 'importance' of C_j to the overall utility

e_{ij} = effectiveness of alternative A_i related to criterion C_j.

(Roozenburg and Eekels 1991)

5. A FRAMEWORK FOR THE SELECTION OF ENERGY SAVING BUILDING COMPONENTS

Following the systems engineering approach the procedure for the selection of energy saving building components consists of the following four main activities:

1. analysis of objectives and constraints that control the selection of energy saving building components, and specification of appropriate performance indicators;
2. development of an 'option space' that consists of combinations of building design(s) and energy saving building components and a parameterization of these combinations;
3. determination of the performance of these combinations;
4. selection of the most desirable combination of building design and energy saving building components.

5.1 Analysis of objectives and constraints

In current practice the starting point for the selection of energy saving building components is found to be underdeveloped. In most cases the design brief contains only few instructions concerning energy use (which is appropriate as the brief is just a short description of the kind of building design that is to be developed); these instructions might vary from a statement of a broad overall objective ('develop an environmentally friendly building') to reference to building codes or specification of clear requirements concerning energy use. However, design teams do not seem to take the time to develop these instructions into a proper list of objectives and constraints, performance indicators, and requirements and goals. The lack of this list results in heuristic, single-attribute decision making on energy saving components (de Wilde et al. 1999).

Obviously, the main objective of the use of energy saving building components is to make buildings more energy-efficient. Yet energy efficiency is only one of many objectives that must be considered in building design; the notion of 'energy efficient building design' as a mono-discipline is clearly fictitious. The objectives that are relevant when making design decisions concerning energy saving building components can be mapped using a (reduced) general 'objective tree' for building design; see figure 1.

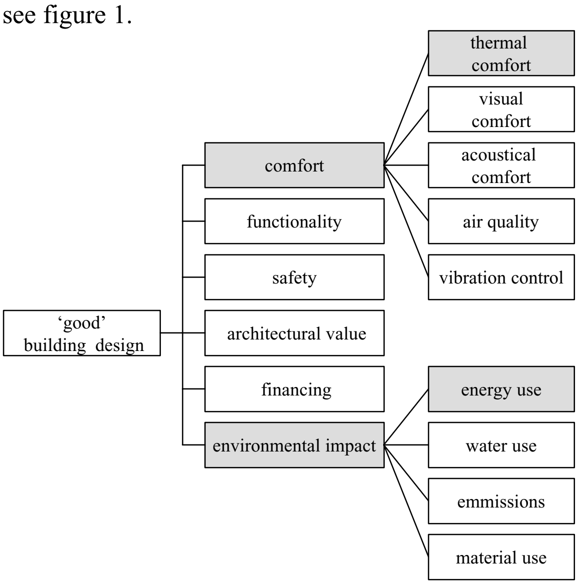


Figure 1: objective tree for building design (reduced)

For energy saving building components the main objective is efficient use of energy; all other building design objectives act as constraints. Of these constraints thermal comfort is most related to energy use. Both energy use and thermal comfort are highlighted in the objective tree.

To capture these objectives and constraints, an extensive set of performance indicators can be used. An overview of some of the possible performance indicators for the objective 'energy efficiency' and the constraint 'thermal comfort' is presented in table 1. Note that these performance indicators are based on an evaluation of the design under a given 'experiment'. Performance indicators are functions of design properties (e.g. U-value), whereas U-value is not a performance indicator by itself. Also note that further specification of these performance indicators is possible (for instance one can discern energy consumption for whole buildings or for rooms, and energy consumption for heating and for cooling). See table 1.

Table 1: overview of some performance indicators for 'energy efficiency' and 'thermal comfort'

Objective	Perf. indicator	Symbol	Unit
energy efficiency	energy consumption	E	J or GJ
	peak heat demand	q	J/s
thermal comfort	predicted mean vote	PMV	-
	predicted percentage of dissatisfied	PPD	%
	discomfort degree hours	ddh	h
	minimum or maximum temperature	T_{min} T_{max}	^{0}C or K

5.2 Development of an 'option space'

Study of recent design projects reveals that in most projects an 'option space' for energy saving building components is virtually non-existent: 80% to 90% of all energy saving components are selected without consideration of an alternative (de Wilde et al. 2001). Hence design teams should be stimulated to broaden their search. An obvious strategy is to generate alternative system configurations by combining a given building design with one or more energy saving building components.

In such a strategy for the selection of energy saving building components it is necessary to consider the building design to be invariant and leave aside the earlier development of this design, hence treat the design information as an input to the procedure. Even as input only the building design can take many shapes, from a design that is defined by a volume and a building function only up to a completely defined existing building for which all details are known (as encountered in renovation projects). However, as the most important phase for the selection of energy saving building components is early conceptual design, this is the design development stage that lies at the heart of this study.

Energy saving building components are existing technical 'solutions'; building designers can choose from an array of possibilities. Yet a random search for an energy saving component mostly leads to consideration of many inappropriate components; a morphological chart can help to arrive quickly at a number of components that might be useful for a specific building design. A total of nine main functions of energy saving building components can be discerned: limitation of transmission losses, limitation of ventilation and infiltration losses, energy storage, utilization of internal heat loads, use of renewable energy (solar, wind, hydro, ...), efficient heating, efficient cooling and miscellaneous (like influencing occupant behavior). Approximately 90 energy saving building components are available to achieve these functions. As example, the 'storage' function part of the morphological chart is show in figure 2.

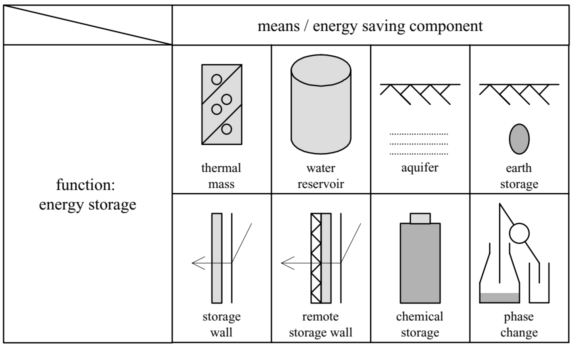


Figure 2: morphological chart for energy saving components showing the function 'energy storage'

Using the morphological chart the design team can make a pre-selection of energy saving building components. This pre-selection remains based on (subjective) preferences; without further evaluation of the performance of the components no well-founded final selection is possible. Note however that evaluation of all possible combinations is not within reach: even for a building with four energy saving components (the average number) the 90 components allow to make more than 60.000.000 combinations (de Wilde et al. 2001).

For each energy saving building component a set of relevant parameters can be defined. The range of these parameters is either defined by the building design or by external factors; for instance the maximum area of the separating wall between a sunspace and the adjacent building is limited by the building design, whereas the COP (coefficient of performance) of a heat pump depends on physics. Parameters that relate to the building design are named 'design dependent parameters'; the other parameters are named 'design independent parameters'.

A catalogue of energy saving components that gives the design team easy access to design-dependent parameters, design-independent parameters and their respective limiting factors will help to speed up the definition of the option space.

5.3 Determination of the performance of all options

Determination of the performance of a building is the traditional field of building performance simulation; however, application of building simulation tools to real-life building design remains problematic. In actual design projects simulation tools are mainly used for optimization and verification, and not to support basic design decisions. Furthermore, the selection of tools seems to be arbitrary; there is no support system in place to guarantee that an appropriate tool is used for a specific design evaluation (de Wilde et al. 2001); yet one tool only must be picked from a whole range (DOE).

Application of computational tools to support the selection of energy saving building components should be aligned with the objectives and constraints that have been identified, and within the option space that has been developed. It should also anticipate the selection process that will follow. This can be realized by setting up a performance matrix, which can be transformed into an assessment matrix during the next step. The columns of the performance matrix are defined by the performance indicators that capture the objectives and constraints; the rows are defined by the elements of the option space (the energy saving components). Now a tool (or combination of tools!) that is able to fill this matrix must be selected. See figure 3.

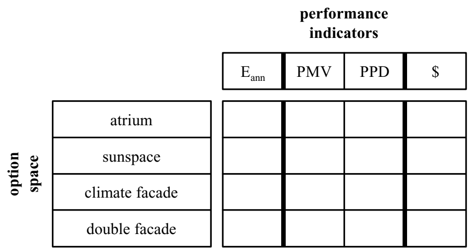


Figure 3: example of a performance matrix

To support the search for tools an enlarged performance matrix can be used that includes all available performance indicators and all available options (the whole search space of all energy saving components). In this enlarged matrix it is possible to map all cells that can be filled by individual simulation tools; the result is a 'footprint' of these tools. Now the cells defined by a set of selected performance indicators and an option space can be used as a filter to find an appropriate (set of) tool(s). See figure 4.

The accuracy of the output produced by the tools must be sufficient to discern the requirements and goals as defined. A surplus of accuracy is easily discarded during the transformation of the performance matrix into the assessment matrix; however, this implies that unnecessary computational efforts have been made.

It is important to note that the output of tools is a performance prediction based on a set of assumptions (concerning building design/operations/climate/…), modeling efforts and computational operations; all these introduce their own uncertainties. However, when it comes to a risk and uncertainty assessment of building performance assessments, we have to acknowledge that this field has been receiving attention only recently (de Wit 2001). As uncertainty analysis for building simulation still needs to go mainstream, it is not yet realistic to add uncertainty to the framework.

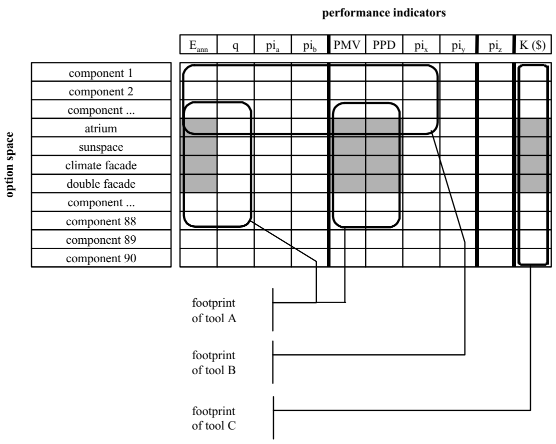


Figure 4: use of an enlarged performance matrix to support the selection of an appropriate (set of) tool(s)

5.4 Selection of the most desirable option

In current practice the selection of energy saving building components is found to be highly intuitive; the choice for a specific component is mostly based on experience and analogy. However, intuition and experience are neither absolute nor objective; moreover, good intuition and experience cannot be transmitted to succeeding generations (de Wilde et al. 2001).

The final step in the discussed framework involves the evaluation of all data in the performance matrix and a selection of the most desirable design option (energy saving building component) based on this evaluation; this makes the selection procedure more rational, transparent and open to discussion.

First, all options must be checked for meeting all requirements; options that do not meet a requirement are ruled out. A preference for one of the remaining options must be based on the extent to which these options meet the goals. This implies that a (subjective) value must be assigned to the data in the performance matrix, thus transforming it into an assessment matrix. In the assessment matrix the extent tp which the options meet the different goals must be measured on the same scale, allowing to compare different performance aspects. For instance energy consumption, thermal comfort and costs can all be measured according to the scale:

0.0 = does not meet the goal;
0.5 = just meets the goal;
1.0 = perfectly meets the goal.

Selection of the most desirable option from the resulting assessment matrix involves making a tradeoff between the relevant performance aspects. This tradeoff is subjective once more. However, by using an additive utility fuction the underlying subjective value structure is made explicit and negotiable. A fictitious example of an assessment matrix with weighting factors and overall utility values is shown in figure 5. The option with the highest value will be selected.

	performance indicators E_{ann}	PMV	K ($)	U(A)
weighting factor ▶	50	20	30	(100)
option space: atrium	1.0	1.0	0.0	70
sunspace	1.0	1.0	0.5	85
climate facade	0.5	0.5	1.0	65
double facade	0.5	0.0	1.0	55

Figure 5: useof an additive utility function to select the most desirable option from an assessment matrix

6. REQUIREMENTS FOR EMBEDDED COMPUTATIONAL TOOLS

The framework for the selection of energy saving building components as presented in the previous paragraph affects computational tools in three ways: through tool selection, through input presented to tools, and through required (computed) output.

The selection of computational tools using 'footprints' of tools and a 'filter' defined by an option space and performance indicators leads to the following consequences:

- Currently there is no tool that has a footprint that covers the whole search space (all energy saving building components) as well as all possible performance indicators; neither is development of such a tool to be expected within the next two or three decades. This means that in most cases a combination of computational tools will have to be used.
- Alternative design options are to be compared on the basis of equivalence. Consequently the use of one tool to determine the performance for one aspect (performance indicator, one column in the performance matrix) is preferable; the use of more than one tool is only possible when taking into account the differences due to (physical)

modelling and computational procedures. In the field of energy simulation and related aspects only a few tools cover a substantial part of the whole search space for energy saving building components: TRNSYS, ESP-r and EnergyPlus (DOE-2/BLAST) all allow evaluation of a fairly broad range of energy saving components, which might explain part of the success of these tools.

- It only makes sense to evaluate the performance of the design options for various performance aspects (energy, lighting, acoustics, costs, …) if and only if these performance aspects are related to actual design objectives and constraints. Hence, the usefulness of product models that facilitate data exchange between different computational tools is strongly dependent on the context of design decisions to be made. Clearly automation of this data transfer alone will not solve the problem of application of computational tools to design; moreover, the data transfer between tools might be too complicated to solve in general. In this light the development of integrated design environments should be guided by principles of openness, flexibility, user driven mappings and data selection, version control and consistency management, and above all allow (remote) multi actor collaboration. For this reason, closed, tightly knit 'integrated design advisors' that provide a multitude of unsolicited performance evaluations seem to have no future.

Computational tools embedded in the framework must be able to predict the performance of design options that consist of the combination of a given building design and one or more energy saving components. This results in the following requirements:

- Embedded tools are to accept a variety of building designs as inputs, and especially be able to deal with conceptual designs. Basically this means that these tools must be able to capture the essentials of a design whether this design is only represented by a few major properties or is described in detail.
- The framework assumes that the option space is defined by a pre-selection of existing energy saving building components. Evaluation of this option space is facilitated by using tools that have pre-defined models of energy saving components which can easily be invoked. Energy saving components can be described in outlines or in detail, too.

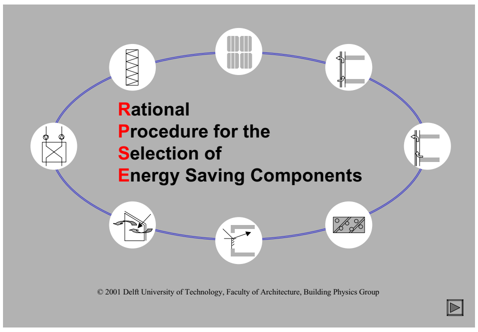
Note that sophisticated computational tools can be used with both coarse and refined models, whereas simple tools intrinsically only cover coarse or lumped models.

The output of computational tools must fit in the performance matrix; moreover, it must have an accuracy that allows one to discern requirements and goals. This has the following consequences:

- Tools should allow one to select and/or modify performance indicators so that they correspond with actual objectives and constraints.
- The performance data generated by tools must allow evaluation and post processing in order to incorporate this data into an overall value assessment. Tools that provide an order of possible design options based on achieved energy savings (like the 'rank' feature in Energy-10) offer little additional value.
- Adjustable accuracy can be useful to bring the computational effort in line with required results.

7. PROTOTYPE ENVIRONMENT 'RPSE'

A prototype incorporating the framework presented in this paper as well as an existing computational tool is currently under development at Delft University of Technology. This prototype, named RPSE (Rational Procedure for the Selection of Energy saving components), is constructed around a 'workflow' tool. RPSE demonstrates the feasibility of an operational design decision support system for the selection of energy saving building components. At the same time RPSE is used to study the interaction between a 'design analysis process template', invoked computational tools and the building design process.



As RPSE is only a prototype, the number of performance indicators and available energy saving building components is still limited. The current version allows to evaluate for energy consumption and thermal comfort, and has an option space that only covers a limited number of passive solar energy saving building components. Currently, the computational tool embedded in RPSE is CAPSOL.

8. CONCLUSIONS AND REMARKS

1. This paper presents a strategy to provide adequate computational support for one specific activity in building design: the selection of energy saving building components. The strategy demonstrates how concepts from systems engineering, engineering design and decision

theory can be used to develop a flexible process support for the deployment of computational tools to inform rational support design decisions. The strategy assumes that the building design is 'fixed' during the selection of energy saving components; however, this does not prevent reiteration with a modified building design.

2. The following consequences for computational tools have been identified:
   - The potential of integrated building models and exchange formats to improve the use and impact of 'analysis tools' on 'design decisions' must not be overestimated. At best this leads to an efficiency improvement, but effectiveness is hardly increased. The main challenge in the development of effective design support is to provide a coupling between relevant design decision problems and appropriate building performance evaluation functions. Only this coupling can ensure that simulation tools are invoced for the correct purpose and at the right moment in the design process.
   - For the moment the idea of one universal computational tool that supports all design decisions is utopian. Instead of trying to incorporate more and more performance aspects into individual tools (energy combined with lighting, natural ventilation, …), efforts should aim towards tools that cover as much of the 'search spaces' (relevant design alternatives, like for instance energy saving components) as possible.
     At the same time tools are needed that can correctly solve specific 'coupled problems' as occur in many heat and mass flow problems; for such specific (design) problems better coupling or even integration of existing tools is required.
   - Tools must be able to cope with both scarce/coarse and abundant/refined design information. Sophisticated tools should offer the advantage that they can work with both models on every granularity.
   - Open selection and custom modification of performance indicators as well as adjustable accuracy help to bring computational efforts in line with the design context.

3. The prototype RPSE demonstrates the feasibility of an operational design decision support system based on the strategy described in this paper.

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