Use of a Knowledge Model for Integrated Performance Evaluation for Housing (Re)Design Towards Environmental Sustainability : A Case Study

ERBAS Irem, BITTERMANN Michael S. and STOUFFS Rudi
Delft University of Technology, The Netherlands
i.erbas@tudelft.nl, m.s.bittermann@tudelft.nl, r.m.f.stouffs@tudelft.nl

Abstract. This paper focuses on the development of a knowledge model in the context of energy efficiency and indoor comfort interventions, their impacts on each other and on architectural design preferences, for instance architectural expression or any spatial functionality aspect, via an existing house case study. In addition, it discusses how this type of model can be used in the framework of a decision support tool and be applied to the design and redesign of dwellings. The model is considered to provide an integral knowledge base for the design professional both to evaluate existing designs and to use it as a support during design and decision making in order to reach a most suitable solution, with optimal performance in terms of indoor comfort, energy efficiency, architectural and overall design performance. In other words, its aim is to enable the assessment of the performance of the end result with respect to design choices, beforehand. In this paper, design performance is modeled by means of fuzzy logic operations embedded in a neural tree structure. This method is able to deal with subjective and vague requirements such as low energy consumption, low overheating risk, high comfort, etc. The method of intelligent information processing is explained and a partial application is presented.

1.   Introduction

Designing is both a goal oriented and a decision making activity. This means it aims to satisfy specific needs by exploring the options to reach the goal. In this process, the designer's primary needs are the information and knowledge that

convey the options for his/her design goals and handle the problems of trade-offs between conflicting goals [1].

Sustainable housing design and redesign is a knowledge-intensive process; it requires different kinds of knowledge coming from diverse experts, such as policy developers, architects, engineers, building physics experts, etc. Multidisciplinary and multidimensional features of design actions and the scattered nature of existing knowledge in this domain turn the decision making and designing phase into a complex process. In order to handle this complexity, engineering and architectural design knowledge and approaches need to be integrated into the (re)design phase as a rational process. In the decision making process of sustainable housing design, a variety of criteria stand out, among others, technical, design, occupants' health and economical. These criteria often interrelate or even conflict, leading to a complex design information space.

An integrated design process that addresses all these criteria entails the need to gain insight into or resolve this complex structure by making the relationships and dependencies of the criteria explicit and subject to computation. Various performance issues - energy, comfort, cost, or other - and their components should be integrally taken into account with respect to the information generated to decide which option is best to prefer and for what reasons. This can be achieved and supported by means of an intelligent assistance, which will provide reasoning to the architect when decisions are being made.

Specifically, this ongoing research asserts that a decision support tool based on advanced computational methods, in combination with the use of existing performance analysis tools, is suitable to overcome this complexity for architects. The decision support tool assists the designer both in selecting appropriate (re)design actions towards improving the performance of the building under design, and in assessing the actual performance improvements resulting from these actions.

The first part requires the explication of the interrelationships between (re)design actions based on a knowledge model being set up by relevant aspects. This type of model represents the knowledge within the domain of energy efficiency and indoor comfort to assist the architect in creating "what-if" scenarios [2]. The second part is about providing the background information to assess performance values and to allow for making comparisons. Within the context of this paper, a knowledge model for an integrated performance assessment is presented.

The weakness of existing assessment tools can be explained as a lack of uncertainty consideration and giving no answers about possible consequences of certain interventions for improvement. Advanced computational support is expected to facilitate an integral understanding of the issue that will be able to respond to the aspects with a broader and reliable basis matching human reasoning.

This paper focuses on the development of a knowledge model with a purpose of providing assistance to judge performance as the basis of such intelligent assistance, within the context of energy efficiency and indoor comfort interventions. Since it is a complex setup to identify and represent all design variables constructing the performance inputs, in this study the overall design performance is limited to three sub-performance criteria; energy, thermal comfort and architectural. Within these, energy performance is evaluated with respect to heat gain, heat loss and specific space heat demand. Thermal comfort performance is assessed with respect to overheating. Architectural performance sub-aspects are identified in the light of the priorities stated by the architect which he was concerned with during his design.

The knowledge model abovementioned is presented with a case study of sustainable housing redesign. In the case study the existing building and three scenarios are compared. One of them concerns redesign, the other two concern alternatives that could have been selected instead of the realized building, simulating the use of the knowledge model during design. For the comparison, first some basic information about the four building alternatives is obtained through analysis, involving a model of thermal behavior. The analysis results are used as inputs for a knowledge model; to compare the project-specific option suggestions and give feedback to the architect in terms of performance before the (re)design is executed. For this purpose an advanced information processing approach, namely intelligent information processing is used. The method is explained and a partial application is presented.

In addition, the paper discusses how this type of model can be used in the framework of a decision support tool and be applied to the (re)design of dwellings. The model is considered to provide an integral knowledge base for the design professional both to evaluate existing designs and to use it as a support during design and decision making in order to reach a most suitable solution, with optimal performance in terms of indoor comfort, energy efficiency, architectural and overall design performance. In other words, its aim is to enable the assessment of the performance of the end result with respect to design choices, beforehand.

2. Method

General approach for integrated performance evaluation is to make use of two models in combination. The first one is to obtain basic feature information about the design. The resulting information is combined with judgments on elemental architectural aspects. Second, the results from the first analysis are used as inputs to a knowledge model that present the performance of the design in abstract

linguistic terms, namely energy performance, thermal comfort performance, and architectural performance.

The first stage involves a model of the thermal behavior of the building [3] providing as its output quantities on specific space heat demand, heat gain, heat loss and overheating percentage. In the knowledge model this information is interpreted with respect to the preferences and goals of the architect, so that alternative designs are judged with precision. The output from the knowledge model yields a number between zero and unity quantifying the overall performance of a design. This means, how well a design matches the demands imposed on the project is provided giving a clear guidance to a decision maker on which design to prefer.

The knowledge model is established using fuzzy logic operations in a neural structure [4]. It is a method to deal with subjective and vague requirements (e.g. low energy consumption, low overheating risk, high comfort, etc.). It is based on specifying an association among a linguistic label and the physical objects. Before elaborating the description of the fuzzy modeling, the case study is introduced, so that the concepts used in the modeling are clarified.

It is noted that the model is transparent in the sense that not only the overall suitability is being computed, but also the performance information on lower level aspects, such as energy, thermal comfort and architecture is obtained.

2.1. Case study

An owner occupied, recently designed and constructed detached house is chosen to further elaborate the knowledge model. This project is considered interesting and relevant to be studied because it incorporates several energy efficiency strategies such as use of heat pump technology, solar panels, double glass and natural ventilation. On the other hand a large transparent facade of the house is oriented towards northeast based on some architectural concerns with respect to the site characteristics (such as privacy of outdoor space, view to the nature).

Another interesting point is the admission of the architect that although the starting point of the project was quite ambitious in terms of achieving a high energy performance house, the end result was not very satisfactory to him. The required EPC [5], calculated by a consultant engineer, was fulfilled, however below the expectancy of the architect. Due to time and budget constraints energy calculations couldn't have been done during the design process. Therefore, other possible interventions, combination of actions and different scenarios are investigated in order to determine how the building's performance could have been improved.

To start the case study, the architect was interviewed to gather more detailed information about the design process and was presented with a questionnaire. This questionnaire was for gaining insight in to what extent the assertion of 'an

intelligent assistance for design decision making is vital' is in line with the view of the architect in practice. This questionnaire included questions about the effective means used in the design decision making process, what level of information he needs in order to improve energy efficiency and indoor comfort performance, the role of consultants, the necessity of a tool as mentioned above and what kind of outputs would be useful for him if such a tool were available.

With the design information thus collected, three new scenarios are proposed in which certain parameters are changed. Energy and thermal comfort performance of the existing situation and the proposed scenarios are evaluated using a thermal behavior model, Passive House Planning Package (PHPP) [3] in this case. The proposed options are given in Table 1.

Table 1. Design changes applied to the existing design to improve its energy performance.

SCENARIOS	CHANGES						
Option 1	SW orienta-tion						
Option 2 *(renovation actions)*	triple glass	Balan-ced HRMV	extra shading from outside	better airtightness			
Option 3	SW orienta-tion	triple glass	Balanced HRMV	extra shading from outside (courtyard)	better airtight -ness	better walll (thicker insulation)	roof extension as a porch on SW facade

In the light of the computed aspects, a comparison analysis is made in terms of energy and thermal comfort performance with the existing design and the new scenarios. Since the options imply an intervention to the architect's design choices, the criterion of architectural performance is also included in the model.

2.2. Knowledge modeling with neural tree as an underlying structure for domain knowledge

A project-specific knowledge model is developed and implemented. This is composed of two parts: a thermal behavior model and a neural model. The former represents the physical domain whereas the latter represents the abstract domain modeling the knowledge. Figure 1 represents how the relevant feature information is processed in the model to generate new performance information.

The basic information gathered from the existing building or the design alternatives is processed for each case one by one, using the thermal behavior model (PHPP in this case) to obtain information about the evaluation-specific properties of the building. In a second step, this information is further processed using a knowledge model to obtain information about the building's performance characteristics. The role of computational intelligence (CI) in this approach is to represent the knowledge in a mathematical model to accomplish the second step. The second step has three stages. The first one is fuzzification, where each of the evaluation-specific features is interpreted with respect to an elemental performance aspect, such as high comfort, or low heat energy demand (level 0 in Figure 4). In the second stage chained logic AND operations [6] are executed to compute the outputs at the nodes at the upper levels, seen in the same figure. In the final stage defuzzification is executed at the uppermost level to obtain the design performance.
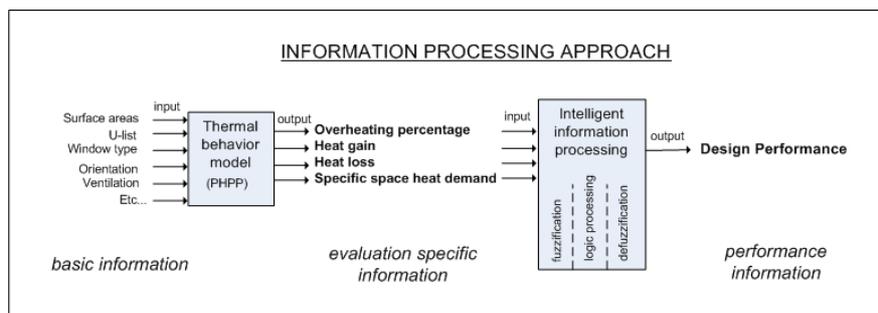

Fig. 1. Information processing in the knowledge model.

In the knowledge model used in this example, the relations between the aspects, that are the *attributes*, were construed as fuzzy logic. The basic reason to use fuzzy logic approach in this research was that the uncertainties and/or imprecision in the attribute relations are well taken care of with the elicitation of more precise outcomes in fuzzy logical computation.

In particular the use of fuzzy neural tree is considered due to its desirable features in terms of handling at the same time a large amount of attribute relations and dealing with imprecision that is inherent in the information. A neural tree is composed of one or several model output units, referred to as root nodes that are connected to input units termed terminal nodes, and the connections are via logic processors termed *internal nodes*. The non-terminal nodes represent neural units and the neuron type is an attribute introducing a nonlinearity simulating a neuronal activity. In the present case, this attribute is established by means of a Gaussian function which has several desirable features for the intended goals; namely, it is a radial basis function ensuring a solution and the smoothness. At the same time it plays the role of a fuzzy membership function in the tree structure,

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which is considered to be a fuzzy logic system as its outcome is based on fuzzy logic operations and thereby associated reasoning [6]. The neural structure is used to decompose the variable of ultimate significance, being the design performance, into its subcomponents. The nodes are intelligent processors, where a fuzzy logic operation occurs. The functionality of the logic operation is to model the performance aspect associated with this node in terms of the nodes connected to it. An example of a fuzzy neural tree is shown in Figure 4. Considering for example the node labeled *experiential performance* it is noted that the node has three inputs as *architectural expression*, *view to nature* and *outdoor space privacy*.

The detailed structure of the nodal connections with respect to the different connection types is shown in Figure 2, where the output of i-th node is denoted μ_i and it is introduced to another node j.
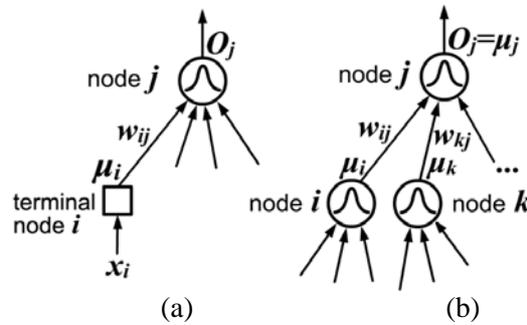

(a)   (b)

Fig. 2. Different type of node connections in a fuzzy neural tree model.

The weights w_{ij} are given by domain experts, expressing the relative significance of the node i as a component of node j. The centres of the basis functions are set to be the same as the weights of the connections arriving at that node, so that the maximum of the basis functions is located at unity. Therefore, for a terminal node connected to an inner node, the inner node output denoted by O_j, is obtained by [7]

$$O_j = \exp\left(-\frac{1}{2}\sum_i^n \left[\frac{(\mu_i - 1)}{\sigma_j / w_{ij}}\right]^2\right) \qquad (1)$$

where j is the number of the node; i denotes consecutive numbers associated to each input of the inner node; n denotes the highest number of the inputs arriving at node j; μ_i denotes the degree of membership being the output of the *i-th* terminal node; w_{ij} is the weight associated with the connection between the i-th terminal node and the inner node j; and σ_j denotes the width of the Gaussian of node j.
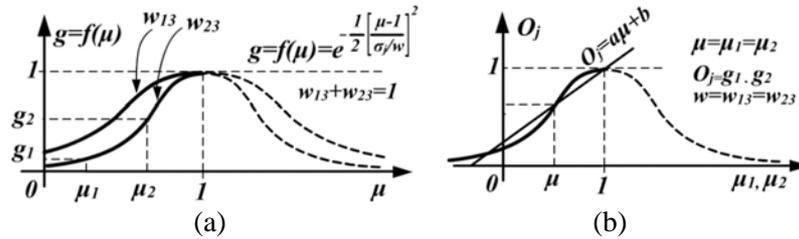
Fig. 3. Fuzzification of an input at an inner node (a);
linear approximation to Gaussian function at AND operation (b).

It is noted that the inputs to an inner node are *fuzzified* before the AND operation takes place as shown in Figure 3a, while the ensuing AND operation is illustrated in Figure 3b. It is also noted that the model requires establishing the width parameter σ_j at every node. This is accomplished by means of imposing a consistency condition on the model [7]. This condition is to ensure that when all inputs take a certain value, then the model output yields this very same value, i.e. $\mu_1 = \mu_2 \approx O_j$. The consistency is ensured by means of gradient adaptive optimization, identifying optimal σ_j values for each node. It is emphasized that the fuzzy logic operation performed at each node is an AND operation among the input components μ_i coming to the node. This entails for instance that in case both energy effectiveness and efficiency are highly fulfilled, then the energy performance is high as well. In the same way, for any other pattern of satisfaction at the model input the performance is computed.

In the figure above, an implementation of an integral knowledge model is given. In this model, the design performance is determined as the final outcome. This is a partial application due to the inherent complexity in a design, the more detailed the inputs are given the more accurate the results are obtained (in Figure 8 an extended version of the model is also presented).
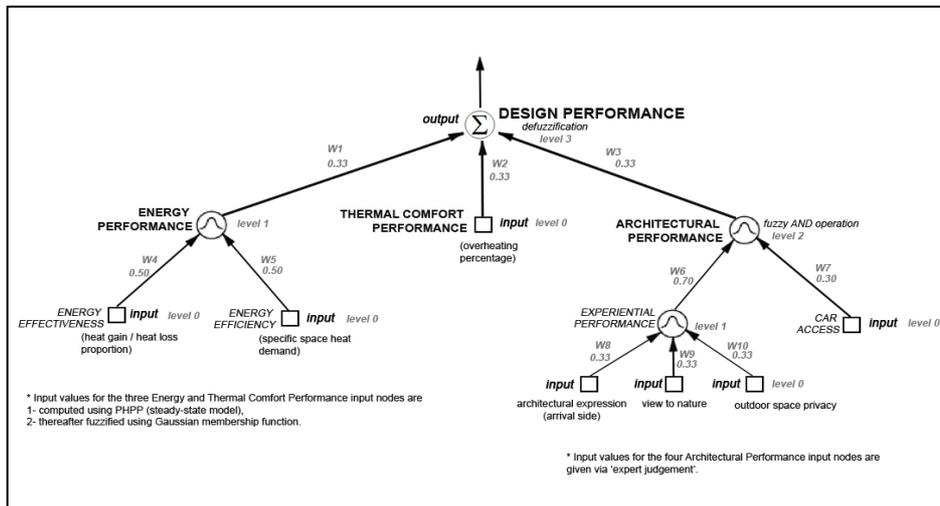
Fig. 4. Reference knowledge model of the case study.

In this model, design performance consists of three performance aspects:

1. Energy performance which is built upon two evaluation specific attributes: heat gain and heat loss proportion (described as energy effectiveness), and heating demand (described as energy efficiency).

2. Thermal comfort performance, which is determined by the overheating percentage.

3. Architectural performance, which is included for the fact that there is an intervention to the final decisions of the architect. This aspect is determined by two attributes; experiential performance (composed of three aspects, architectural expression, view to nature and outdoor space privacy) and car access.

As seen in the Figure 4, where W1=W2=W3=1/3, the design performance is considered as equally dependent on the energy, thermal comfort and architectural performance. This is an expression of the preferences of an architect for the present case, i.e. it is an instance of the design knowledge being modeled.

In order to arrive at a high accuracy in the determination of such knowledge, well known techniques for prioritization, such as Analytical Hierarchy Process (AHP) can be used. The AHP method is a technique developed by Saaty (1980) to compute the priority vector, ranking the relative importance of factors being compared. The only inputs to be supplied by the expert in these procedures are the pair-wise comparisons of relative importance of factors, taken two at a time

[8]. Due to the low number of input variables, namely maximum three for every node, the importance vector assignment is done without the use of AHP in this case. This is sufficient, because the expected inconsistency of the judgment matrix is expected to be low.

In general, every performance aspect may have a different level of significance for the final outcome (design performance in this case), i.e. it depends on the circumstance of the project. The designers should identify this priority by giving weights to the relations between the aspects. It is noted that knowledge encompasses not merely the information on what variables are effective on the performance, but also includes the information on the relative importance among the variables. These relations were given weights, which take care of the hierarchy of influence that different variables have on the final result.

3. Results

In Figure 5 the results of the performance calculations are given. From these results it is interesting to see that design option 2 is superior over the others in terms of *design performance* ("overall performance"), whereas option 3 is superior over others in terms of energy performance. Option 2 possesses the highest design performance value because in contrast to option 1 and 3, the architectural aspects remained the same, so the model yields the same architectural performance value compared to the existing house. The values of the aspects of the architectural performance in the model are kept as high values for the existing case because the aesthetical or functional decisions which have already been made by the architect are deemed favorable in this case. In the first and third scenarios more radical changes are applied such as changing the orientation as what-if scenarios with an aim of maximizing the energy performance (for instance to increase the solar gains). Therefore it is considered that this change would have a reflectance on the aspects which set up the experiential performance and the accessibility on site. This resulted in lower values in comparison to the existing case.
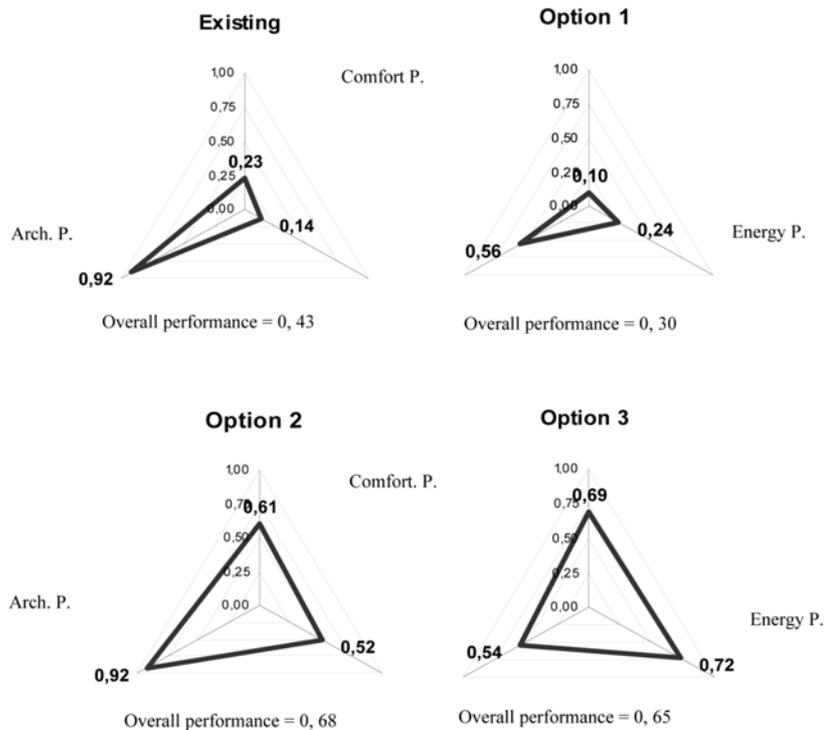
Fig. 5. The results of the neural model for the performance calculations.

This is automatically calculated in the overall design performance. This is the reason why the third scenario did not have the highest design performance. It should also be noted that the sub-performance aspects of design performance possess equal weights in this example. In case a higher value is given to energy performance in comparison to thermal performance and architectural performance, the design performance comparison changes. This is an issue of priority which should be decided by the architect in consultation with energy and comfort experts.

The Figures 6 (a,b) and 7 show the membership functions used to transform the crisp input data to fuzzy information at the model input. These specify the concepts of energy efficiency, energy effectiveness and overheating percentage (coming from PHPP). By means of these functions it is possible to trace the performance of the four different cases at the input level. The sigma parameter of the Gaussians shown in Figures 6 (a, b) and 7 is used to specify the uncertainty tolerated at the model input. In this case study the values for preliminary sigma are determined by the expert judgment. Identifying the sigma based on scattered data modeling is an interesting relevance.
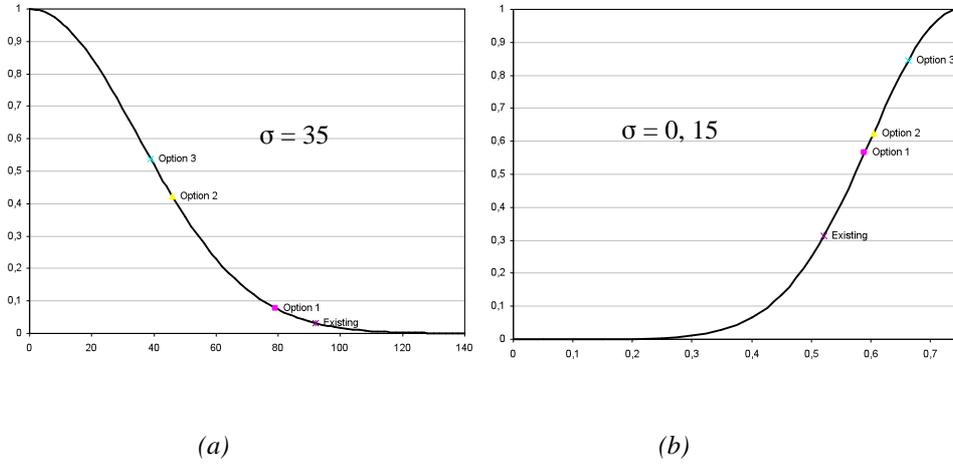
(a)   *(b)*

Fig. 6. Fuzzification for energy efficiency (a);
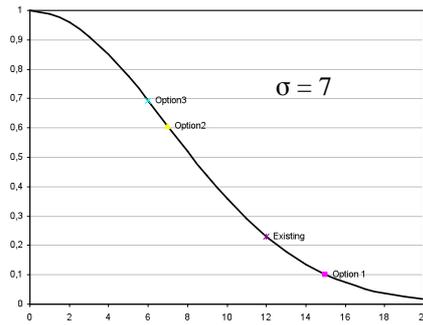*Fuzzification for energy effectiveness (b).*

Fig. 7. Fuzzification of overheating percentage

The role of heat loss and gain and their proportion is significant in energy performance calculations. Within the scope of this example, this proportion is assumed as the energy effectiveness whereas the specific space heat demand is given as the energy efficiency together with forming the energy performance. In addition, looking at the comparison results it is also concluded that compactness (surface to volume ratio) of the building plays a big role in the energy performance. Although the energy improving actions were maximized in the third scenario the overall specific space heat energy demand could not reach at the passive house level. This is due to the courtyard formation which makes the building less compact and yields greater transmission losses through the larger surface area.

4. Possible expansion of the model

Figure 8 is an example to show the possibility of considering additional elemental requirements and performance outcomes.
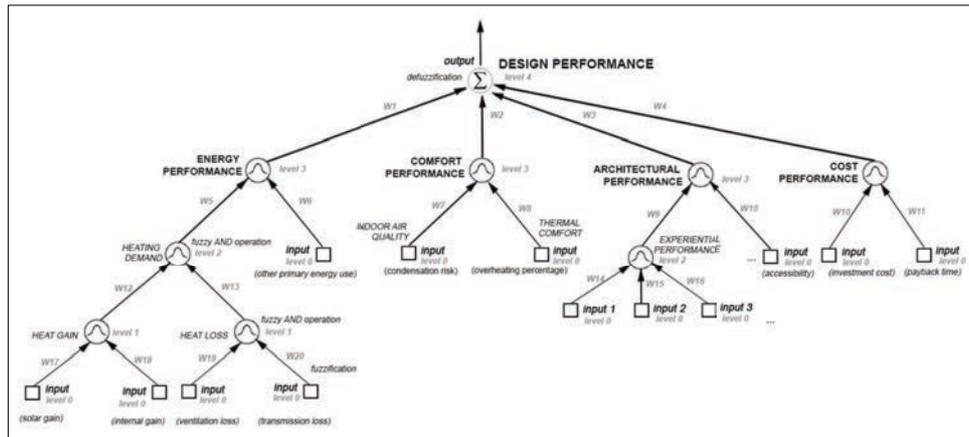

Fig. 8. An abstract representation of integration of complex
knowledge into hierarchical tree structure.

Within this paper the knowledge model for the assessment is limited to a few variables in order to make it simpler to show the approach more clear. The approach presented here is extendible including more variables together with different experts such as safety, cost performances and all the inputs that define the performance criteria. This would offer a new medium to different specialists to design and work together. In the following stages of the research a knowledge model which will provide the architects with alternatives to choose a right strategy will be constructed. This model is considered to be capable of searching for possibilities of improvement from the library of actions based on existing knowledge, analyzing the consequences of intervention actions and providing ways to trace back in the design (iterative generation and analysis process).

5. Conclusions

An information processing approach is presented in the domain of architectural design with a special concern on energy and comfort issues. The knowledge model and associated computational approach described provide information on the performance of a design in abstract terms which are meaningful to the architect for decision making, such as *design performance, thermal comfort performance, energy performance*, etc. Added value of such an approach is treatment of the complexity, so that a number of elemental knowledge and information pieces are integrated for enhanced precision in the evaluation. This approach is verified through the case study. The results show the difference in the performance among the alternative designs, clearly indicating which design is to be preferred and for what reasons. In this case it turned out that renovating the existing house outperformed the other alternatives (0.68) regarding the design performance. The alternative where the orientation of the house is changed as well as the envelope is improved performed less in terms of design performance (0,65), while it outperformed the renovation solution regarding energy performance (0,72 vs. 0.52). From the results it is seen that the superiority of the renovation solution as to design performance is due to its outstanding architectural performance (0.92 vs. 0.54). It is noted that the more detailed the model is established, the more accurately the reason for preferring a design alternative over others is to be traced.

The model is flexible to be expanded. This allows for integration of diverse knowledge into a unified structure, so that the approach is deemed suitable for enhancement of working together in complex decision domains.

6. Acknowledgements

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