A Computer Aided Design Model for Climate Responsive Dwelling Roof

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Abstract. As a consequence of growing concern about the future of the world's energy resources, there is an increasing pressure on architects to both create sustainable design and meet a diverse range of often quite stringent performance criteria. This is inspiring a wealth of new computer-aided architectural design approaches. Generation and optimization take a lot of the issues traditionally dealt with late in the design process and bring them right up front into the formative stage and into domain of the architect. This paper presents a conceptual computer aided design model for climate responsive dwelling roof. It is based on generation and optimization paradigms; which is diametrically opposite to conventional simulation. Given the required inputs, this model automatically generates prescriptive quantitative information to design roof to achieve optimum thermal comfort in warm humid tropics. The rational and methodology used to develop the proposed model is outlined and the implementation of model is illustrated for climatic and technological contexts of India and Australia.

1. Introduction

Achieving the high level of energy efficiency and performance being demanded of our buildings is requiring new approaches to the design process. Whether referred to as climate responsive, bioclimatic or sustainable design, it integrates the architect's aesthetic endeavours and architectural science principles to create functional and energy efficient designs. Consequently, it is imperative that each part or element of a dwelling is designed to maximize favourable effect on the indoor climate and minimize harmful effect to such an extent that they can be tolerated. At the same it is critical for an architect to optimise the performance of his or her design to provide good value of the investment.

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Research in computer-aided architectural design developed primarily with the aim to assist different aspects of building design [1, 2] and over the last five decades or so, three clear paradigms have successively emerged [3]. First, design was conceived of as a problem solving activity [4]. While CAD proved to be effective in handling well-defined problems, in managing ill-defined problems it was severely limited. Then, as a result of developments in symbolic computing and artificial intelligence, designing was seen more as a knowledge-based activity [5, 6]. However, the fundamental limitation of knowledge-based design is that there is, in general, no guarantee that a knowledge-base is complete and accurate. Since last one decade there is a growing consensus that designing must be treated as a fundamentally social activity (collaborative design)-a matter of multiple, autonomous but interconnected intelligences in complex interaction [7]. What may appear to be shifts in paradigm actually represent convergence on a single, original aim : the use of computers to assist designers (and others who are involved in the design process) to assess the quality, desirability, and the implications of their creations.

CAD models based on procedural computing can be broadly classified into three categories : *simulation*, *generation,* and *optimization* [8]. Simulation is typically used towards the end of building design process mainly to check well-developed solutions against mandatory or recommended standard. In such situation the majority of the design parameters is known or has been determined by the design team. At the formative design stage, where even the basic form of the building has not yet been finalized, the sheer number of unknown parameters at this stage is considered to render detailed computational simulation of modicum assistance. Furthermore, most of the decisions that affect comfort and energy use occur during the formative design stage and the efforts required to implement those decisions at this stage are smaller compared to the effort that would be necessary toward the end of the design process.

This paper argues that generation and optimization can be effectively used for well defined problems. The design of a dwelling is a complex and cannot be solved as a single overall problem. The usual approach is to decompose the overall problem successively into smaller subproblems until a level is reached where we are capable of solving the subproblems. Then find solutions to each of the subproblems so as to successively solve the overall problem, i.e. integrating the various parts into a coherent whole. The design of dwelling is, therefore, formulated as an eight-stage generation and optimization problem [9], each stage corresponding to crucial decision: 1) orientation, 2) form, 3) roof, 4) walls, 5) openings, 6) shading devices, 7) floor and 8) enclosure system. Consequently, all the technical requirements are slowly established during the design process.

In designing a roof, an architect has to consider many factors : aesthetic, thermal performance, rain, fire protection, cost, availability and maintenance. In addition recyclability of materials, hazardous materials, life-cycle expectancy and design options as they relate to the environment need to be considered. Consequently, the design of roof is a complex and multifaceted problem. The principal need is for a direct design aid which can generate feasible solutions and tradeoff performance in conflicting requirements and prescribe the optimum solution. If generation and optimization can be applied with actual building roof materials and insulation as parameters then the potential for design generation based on performance criteria is possible. It offers the opportunity to the architect to work with more complete and correct information at the formative stage.

2. Generation

The idea of *generative model* is traced back to Aristotle and has a long and varied history [10]. They played important roles in philosophy, in the evolution of literary and musical theory, and in the development of engineering and architectural design methodology. Generative systems are now seen to be at apex of contemporary architectural practice [11]. Despite the lack of a clear definition and formal methods for its implementation, its significance is now widely recognised by architect and design researchers [12]. Grammar-based generative techniques exploit the principle of database amplification, generating complex forms and patterns from simple specification. G*enerative models* are also called production systems (based on the direct analogy with Chomsky's language models) and shape grammars when applied to architecture. Generative design is also constraint driven parametric search. Some of the examples of generation based climate responsive design are for fixed external sunshades [13], solar envelopes [14], daylighting [15] and stadium roof [16].

In *generation,* the computer is used to explore the consequences of recursive application of a set of decision rules. By their nature, generative models provide a range of solutions that collectively demonstrate all possible design options which satisfy the prescribed rules or criteria. Thus, some decision making is internal to the model but it is not purposeful; all valid decisions are equally acceptable. The results may be evaluated to ensure that they conform to some set of constraints, but they will not be ranked in any way. To control the generative process so that not all (and this "all" could be very large indeed) but only the best solutions are generated requires that the objectives as well as the decisions be contained within the model. This entails application of optimization.

3. Optimization

In *optimization*, the computer is used to prescribe a design solution or solutions in order to achieve a specified objective as closely as possible. The decisions are chosen on the basis of their effect on the performance of the solution in relation to the specified objective. Some evaluation and decision making are internal to the model and are purposeful; decisions are chosen according to their ranking on an explicit measure of effectiveness. Optimization models effectively search the whole field of feasible solutions and identify those best suited to the architect's stated objectives. Design options can be obtained by identifying near-optimal as well as optimal solutions. Goldberg [17] suggested that the optimization methods could be divided up into three groups : enumerative methods, calculus based methods and random (stochastic) methods.

When there is one criterion there is a unique set of decisions which produces the best performance in that criterion. However, when there is more than one conflicting criteria the notion of a unique set of decisions no longer applies and the concept of a best performance needs to be replaced by a more general idea. There must be some conscious or unconscious process of balancing or trading off performance in various design criteria one against another. One powerful concept in multi-criteria design optimization is that of Pareto optimality [18, 19]. The set of Pareto solutions is known as the set of non-dominated or non-inferior solutions. A non-dominated (Pareto optimal) solution is one for which no other solution exists that will yield an improvement in one criterion without causing a degradation in at least one other criterion. The best solution must lie within the Pareto set. Multi-criteria Pareto optimization has following advantages :

1) It can handle nonlinear, discrete information.
2) It can handle a variety of objectives.
3) It models the problem in an easily comprehensible manner.

Every building is usually a compromise between a vast array of competing requirements. Thus, when faced with many competing criteria, the best design solution is often the "least worst" option.

4. Generation and optimization

It has been argued in this paper that the architect's principal need is for prescriptive-information that expresses the design options and addresses the problem of tradeoff between conflicting design objectives. Generation is necessary to create the solution set to be searched, and optimization is necessary to evaluate the performance and to trade-off between conflicting design goals. Thus, generation and optimization offer the most systematic models for CAD because they incorporate all of design activities, making design decisions, performance evaluation and satisfying the objectives.

A design process based on generation and optimization is composed of the following components :

1) A design schema.

2) A means of creating variations.

3) A means of selecting desirable outcomes.

Marsh [20] breaks the process down into similar components but with greater emphasis on performance measurement as "*Configuration variation*" (1 & 2 combined), "*performance metric*" (aspects of 3), and "*decision making response*"(3).

5. Proposed CAD model for roof

The climate responsive design of roof (*design goal*) can be defined in terms of design *objective* as "control radiant and conduction heat". This objective must be satisfied to achieve the design goal. The *performance variables* must acquire values within certain ranges which will satisfy the objective. These ranges may be stated in specific terms as constraints or in general directional terms as target. This can be as simple as a single number as roof ceiling surface temperature or a scaled index. However, it must be possible to construct an unequivocal numerical test by which to determine an ordinal relationship between the thermal performances of different roof configurations. This usually means to judge thermal performance of a given roof to be better/worse, desirable/undersirable, greater/lesser or above/below another. In the proposed model thermal performance index (TPI*) is used, the worst roof, the galvanized iron roof is rated at TPI* of 0% and the roof satisfying the comfort needs for the given climate is rated at TPI* of 100% [21].

The *design variables* must be assigned some values to collectively describe a design (*system*). This is some aspect of the physical configuration of the roof model that will be manipulated or changed. This could be materials properties of each layer of roof or the entire roof geometry. This aspect is usually the real focus of the problem as the automated manipulation of complex geometry is still a developing field. More generally, performance variables are related to the required functions and design variables to the form or structure of the design.

The crux of design process lies in the correct mapping between the design and performance variables so as to achieve the objective or goal. A performance variable is often influenced by more than one design variable. The converse is also true : one design variable is likely to influence more than one performance variable. The performance and decision variables thus interact in complex ways and the relationships between them are not always obvious. Conceptually it is illustrated in Figure 1.

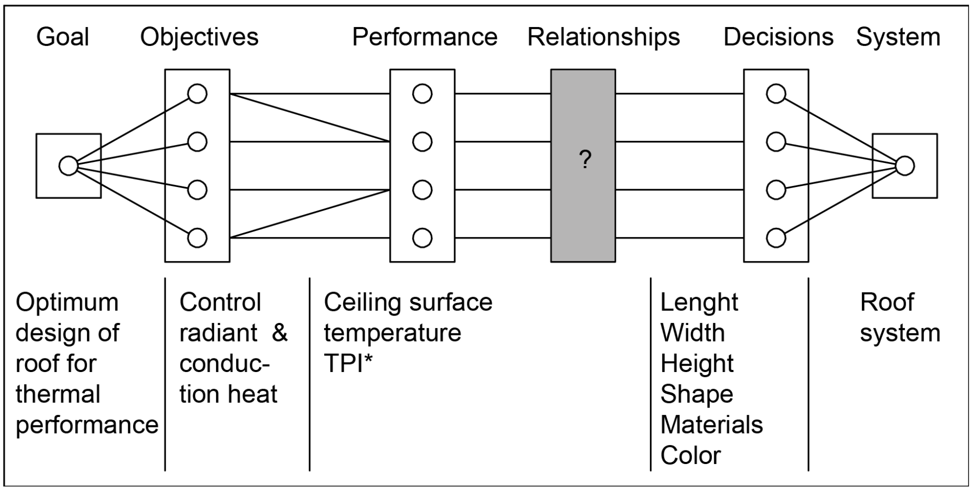

Fig. 1. A conceptual model for designing roof in a given climatic context.

5.1. The generation module

The generation module aims to provide design information on feasible solutions. In the past, there were far fewer roofing materials to select from than there are today. Although there is a wide range of roofing materials available for dwelling construction, usually practical and aesthetic considerations tend to limit the range from which to choose. This range can be called *preferences* of the architect for a particular application.

Organization of knowledge within the framework of some system of types enables us not only to understand but also to generate architectural objects that can be constructed within design worlds. This is done by recognizing instances of abstract types and applying the knowledge to see them as standing for instances of architectural vocabulary elements (or parts of such elements) in the construction world. In case of roof, Thiis-Evensen [22] gives a vocabulary of roof themes, dome, barrel vault, gable, shed and flat. Usually, dwelling roof is either flat or pitched.

A physical system is defined as a collection of functionally interconnected physical objects [10]. A roof can be regarded as a physical system. More formally, it can be said that the roof can be broken down into some set of elementary parts which can be regarded (for our purposes at hand) as indivisible. In addition to specifying the properties of the element, we can also specify the relationships in which those elements stand to each other. This opens up the possibilities not only of ascribing physical properties to the roof as a whole, but also of ascribing physical properties to its parts. It is the positioning of the parts or elements that governs the climatic response of the roof.

For generating alternative solutions decision rules are established based on replacement rules of English grammar described by Mitchell [10]. Grammarians of spoken language, for example, often set out sentence schemata like :

The __________ is green.

Then they specify the type of word substitutable for the blank, in this case a noun. Thus the schema might be expressed: *The **Noun** is green.*

Noun is a variable ranging over all the English nouns : substitution of any instance of an English noun, such as *grass*, yields a grammatical English sentence. Similarly, a possible arrangement of key elements of roof can be defined based on topology and geometry and each arrangement can be identified as a *template* and each element can be identified by a *label*. For example, a possible arrangement of key elements of a roof can be expressed like : ***Cladding*** → *Attic* → ***Insulation*** → ***Ceiling***

A *template* provides the roof schemata and *label* provides the type of material substitutable. Then specify a list of *preferred* materials substitutable for the *Cladding*, *Insulation* and *Ceiling*. In addition to replacing materials, properties of materials can be also replaced or modified in this process. For example, while replacing materials for insulation it is possible to increase its thickness or resistance, since it is one of the possible ways of improving thermal performance of roof. To do this it is necessary to test the performance of the roof and see if more insulation is required. Similarly, colour of external surface can be varied to improve performance. Thus, the template tells how to compose the elements of roof correctly, they encode knowledge of how instances of this type of roof are put together and the list or lexicon of preferred materials tells how to parameterize elements and assign values to properties.

To illustrate the concept of generation module, a light weight pitched roof is considered as a system of cladding, structure, air space or attic, insulation and ceiling. Cladding, facing the sky, provides a defence against the sun and precipitation, structure provides support and sometimes it is integrated with the roof, airspace or attic provides barrier to heat flow, additional insulation also provides resistance to heat flow and ceiling provides the covering surface and sometimes also acts as insulation, it is usually supported by or integrated with the structure. Six templates showing possible arrangements of the key elements, defined based on topology and geometry are given below and are illustrated in Figure 2.

Templates : Labels

Template 1 : ***Cladding***

Template 2 : ***Cladding*** → *unventilated attic* → ***Ceiling***

Template 3 : ***Cladding*** → *ventilated attic* → ***Ceiling***

Template 4 : ***Cladding*** → *ventilated attic, low emissivity attic* → ***Ceiling***
Template 5 : ***Cladding*** → *ventilated attic* → *Insulation* → ***Ceiling***
Template 6 : ***Cladding*** → *ventilated attic, low emissivity attic* → *Insulation* → ***Ceiling***

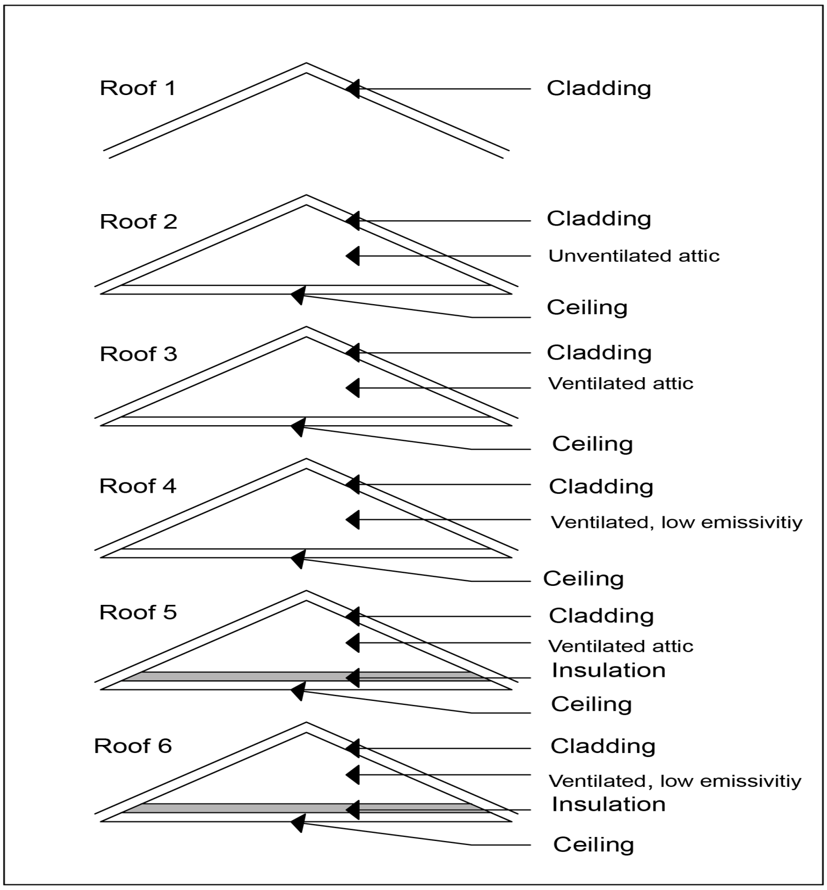

Fig. 2. Six templates of light weight pitched roofs.

In these examples, cladding is predominant, which primarily serves to provide shelter from weather. Thus material for cladding can be used to identify a roof, for example, terra-cotta tile roof, metal roof, concrete roof, etc. Architects then can select the preferred materials for cladding and for some other crucial element, ceiling. This preference based approach for generating has the advantage of giving freedom to architect to select materials and of controlling indiscriminate generation of alternative roofs.

5.2. Optimization module

The optimization module aims to address the problem of finding the optimum roof solution from a large number of feasible solutions produced by the generation module. Probably the first decision confronting an architect is the selection of a suitable objective or objectives to be used to find the optimum solution. These objectives determine what the roof system will achieve and what is desired of the system. Thus, there may be a single objective such as control of radiant heat with the aim being to find a solution which maximizes thermal performance index (TPI*% scale) or minimizes the excess ceiling surface temperature (= the ceiling surface temperature - the room air temperature). Or, there may be many disparate or non-commensurable objectives such as minimize both excess ceiling temperature and cost. This latter class of problems is called multi-criteria optimization problems.

The generation model produces a non-dominated Pareto set of solutions, because by virtue of the design problem, for every design there is no alternative design which will improve performance in controlling radiant heat gain as well as in other criteria, for example cost. In reality the best solution has to satisfy more than one objective specified by the architect and other participants in the design process. An acceptable solution considering other performance criteria would lie between exclusive best and worst design for controlling radiant heat gain. This middle ground is traced through multi-criteria Pareto optimization.

To rank the predicted performances of two or more solutions numerically, it is usually necessary to interpret the multi-valued performance representation in terms of a single-valued criterion that summarizes its contents. Performance-indices are defined at individual objective level and are discipline specific. It is necessary to combine the separate performance assessments into a composite or an overall performance evaluation for a computational optimization strategy. The conventional approach of multi-criteria optimization utilizes weighting techniques to deal with this problem. Weighting factors can be interpreted as "global" numeric modification factors that aim to represent relative degrees of criticality or importance in a multi-criteria optimization field. Mahdavi [23] suggests that in a motivated design environment, where reliable data are available on the integrative experiential indices, the use of weighting strategy is appropriate. In collaborative design environment also, the weighting system is one of the effective strategies for performance evaluation [24]. Typically, weighting system must be set up prior to engaging in the design process, and cannot respond to changes in preferences arising from the dynamic unfolding design process. The weighted performance of the solution C is mathematically expressed as :

$$C = \sum_{i=1}^{P} w_i z_i(x)$$

w_i = A weight attached to the performance $z_i(x)$ in each of P criteria.
$z_i(x)$ = Performance in a criterion x.

By making the sum of weighting factors equal to one and all the indices expressed in percentage scale, the value of weighted performance will be in percentage scale. The system that best satisfies the design criteria is the system with the highest weighted performance. Other types of index value and types of weighting can be used; however, this very simplified nondimensional technique illustrates the concept. Thus, a multi-criteria problem is reduced to a single criterion and finally a prioritized ranking of solutions can be prepared, Figure 3.

Roofs / Criteria						
Thermal Performance						
Cost						
Embodied Energy						
Life-cycle cost						
Fire resistance						
Structural Performance						
Weather Resistance						
Overall weighted Performance						

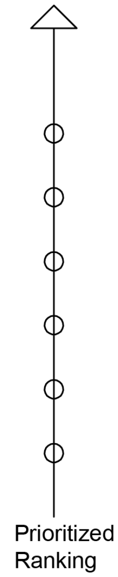

Fig. 3. Optimization matrix for roof, where single criterion or multi-criteria can be considered.

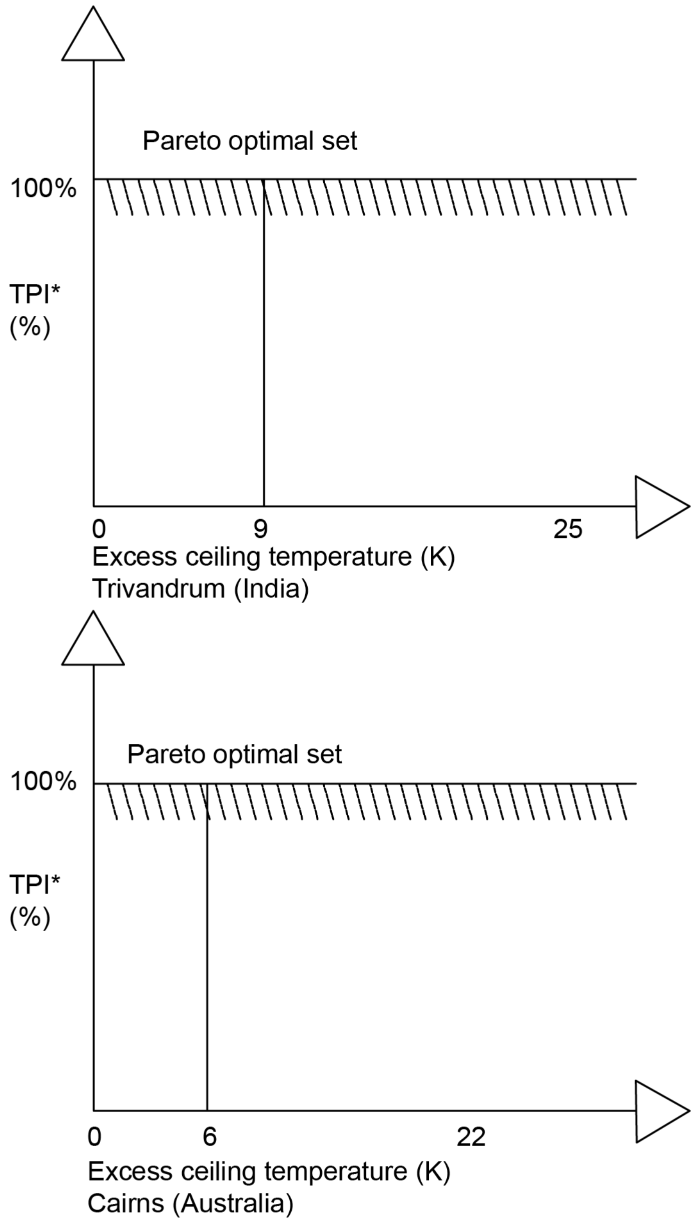

Fig. 4. Roof design goals for two places.

The proposed CAD model is executed for climates of Trivandrum in India and Cairns in Australia. Commonly used roof materials are selected for the respective places. The aim is to generate feasible alternatives and to determine which alternative(s) to choose to optimize control of radiant heat gain of the resultant roof design. The design targets for each in terms of excess ceiling temperature, is 9 K for Trivandrum and is 6 K for Cairns, in other words the solutions with 100% TPI* are sought, Figure 4.

Table 1. Alternative roof configurations and their performance (TPI %) during March in Trivandrum (India).

CEILING	ALT. NO.	TEMPLATE CODE	TERRA-COTTA TILE	CONCRETE TILE	RC L PANEL	AC SHEETS	GI SHEET	AL SHEET
None	1	1	14.49	11.75	17.17	17.48	2.43	39.12
Timber	2	2	94.57	94.29	95.56	94.54	93.14	103.45
	3	3	100.73	100.53	101.56	100.64	99.69	108.17
	4	4	117.13	117.09	115.78	116.74	116.56	120.35
	5	5	114.56	114.50	112.98	114.13	113.86	118.39
	6	6	120.83	120.81	119.75	120.53	120.45	123.16
Plywood	7	2	91.24	90.88	87.10	90.43	88.65	100.50
	8	3	98.78	98.55	95.15	98.03	96.87	106.45
	9	4	117.39	117.35	114.97	116.96	116.76	120.89
	10	5	114.47	114.41	111.86	113.97	113.67	118.64
	11	6	121.52	121.50	119.35	121.20	121.10	123.70
Gypsum	12	2	106.88	106.74	103.53	106.23	105.51	112.67
	13	3	110.21	110.10	107.16	109.61	109.08	115.25
	14	4	117.37	117.34	118.33	120.25	120.12	123.29
	15	5	115.24	115.20	116.36	118.35	118.17	121.86
	16	6	120.69	120.67	121.42	123.23	123.17	125.21
Particle board	17	2	96.15	95.90	97.26	101.44	100.28	108.84
	18	3	101.65	101.48	102.63	106.31	105.56	112.63
	19	4	116.78	116.75	117.80	116.40	116.22	120.12
	20	5	114.27	114.21	115.18	113.82	113.57	118.20
	21	6	120.50	120.48	121.26	120.20	120.11	122.93
Hard board	22	2	93.01	92.64	88.72	93.12	91.23	102.51
	23	3	100.89	100.64	96.63	100.44	99.34	108.15
	24	4	115.00	114.95	116.13	118.13	117.95	121.70
	25	5	111.88	111.82	113.18	115.36	115.08	119.60
	26	6	119.38	119.36	120.21	122.06	121.97	124.51

Note: TPI rating is based on roof shape factor of 0.2, RC – reinforced concrete, AC – asbestos cement*

PROPERTIES OF MATERIALS			
Cladding	**Thickness (mm)**	**Ceiling**	**Thickness (mm)**
Terra_cotta	15	Timber	20
Concrete tile	15	Plywood	6.4
Reinforced Concrete L panel	30	Gypsumboard	12.5
Asbestos Cement sheet	6.25	Particle board	18
Galvanized Iron sheet	3.2	Hardboard	12.5
Aluminium sheet	3.2		

For Trivandrum six cladding materials and five ceiling materials are selected. Table 1 presents thermal performance for one hundred and fifty-six alternative solutions during the hottest month of March in Trivandrum. From these figures it is easy to identify the best solution(s) for each type of cladding material. For instance, terra-cotta tile roof, alternatives number 3, 23, 18, 12, and 13 satisfy the target of 100% TPI*. In addition, the quantitative information presented for every solution is useful to compare the alternatives and if better performance is required other solutions can be adopted.

Table 2. Alternative roof configurations and their performance (TPI %) during January in Cairns (Australia).*

CEILING	ALT. NO.	TEMPLATE CODE	CONC. TILE	TERRA-COTTA TILE	TIMBER SHINGLE	AC SHEETS	GI SHEET
None	**1**	**1**	14.32	10.84	50.56	14.63	16.24
Plaster board	**2**	**2**	83.27	83.87	89.72	83.94	87.22
	3	**3**	90.03	90.48	94.10	89.98	92.91
	4	**4**	105.93	106.05	106.6	105.58	107.15
	5	**5**	108.26	105.62	108.68	107.94	109.86
	6	**6**	109.2	109.26	111.62	111.23	112.13
Plywood	**7**	**2**	85.03	85.62	90.43	85.1	88. 37
	8	**3**	90.99	91.43	94.52	90.65	93.57
	9	**4**	105.88	106	106.53	105.53	107.12
	10	**5**	108.17	108.26	108.59	107.86	109.19
	11	**6**	111.37	111.42	111. 52	111.13	111.98
Timber board	**12**	**2**	80	80.75	87.21	80.58	84.1
	13	**3**	87.8	88.30	92.18	87.54	90.68
	14	**4**	105.19	105.32	105.93	104.84	106.51
	15	**5**	107.69	107.79	108.15	107.37	108. 76
	16	**6**	111.12	111.17	111.28	110.87	111.77
Polystyrene	**17**	**2**	100.41	100.61	101.81	100.02	102.21
	18	**3**	102.14	102.31	103.26	101.76	103.78
	19	**4**	108.64	108.72	108.98	108.36	109.65
	20	**5**	110.07	110.14	110.31	109.81	110.82
	21	**6**	112.11	112.16	112.12	111.81	112.51
Wood wool	**22**	**2**	90.48	90.85	94.19	94.99	97.61
	23	**3**	94.32	94.6	97.09	94.28	96.85
	24	**4**	105.94	106.04	106.48	105.63	107.08
	25	**5**	107.89	107.97	108.25	107.62	108.84
	26	**6**	110.68	110.72	110.81	110.46	111.34

Note: TPI rating is based on roof shape factor of 0.2*

PROPERTIES OF MATERIALS			
Cladding	**Thickness (mm)**	**Ceiling**	**Thickness (mm)**
Concrete tile	16	Plaster board	12
Terra_cotta	16	Plywood	12
Timber shingle	16	Timber board	6
Asbestos Cement sheet	6	Polystyrene	25
Galvanized Iron sheet	3	Woodwool	25

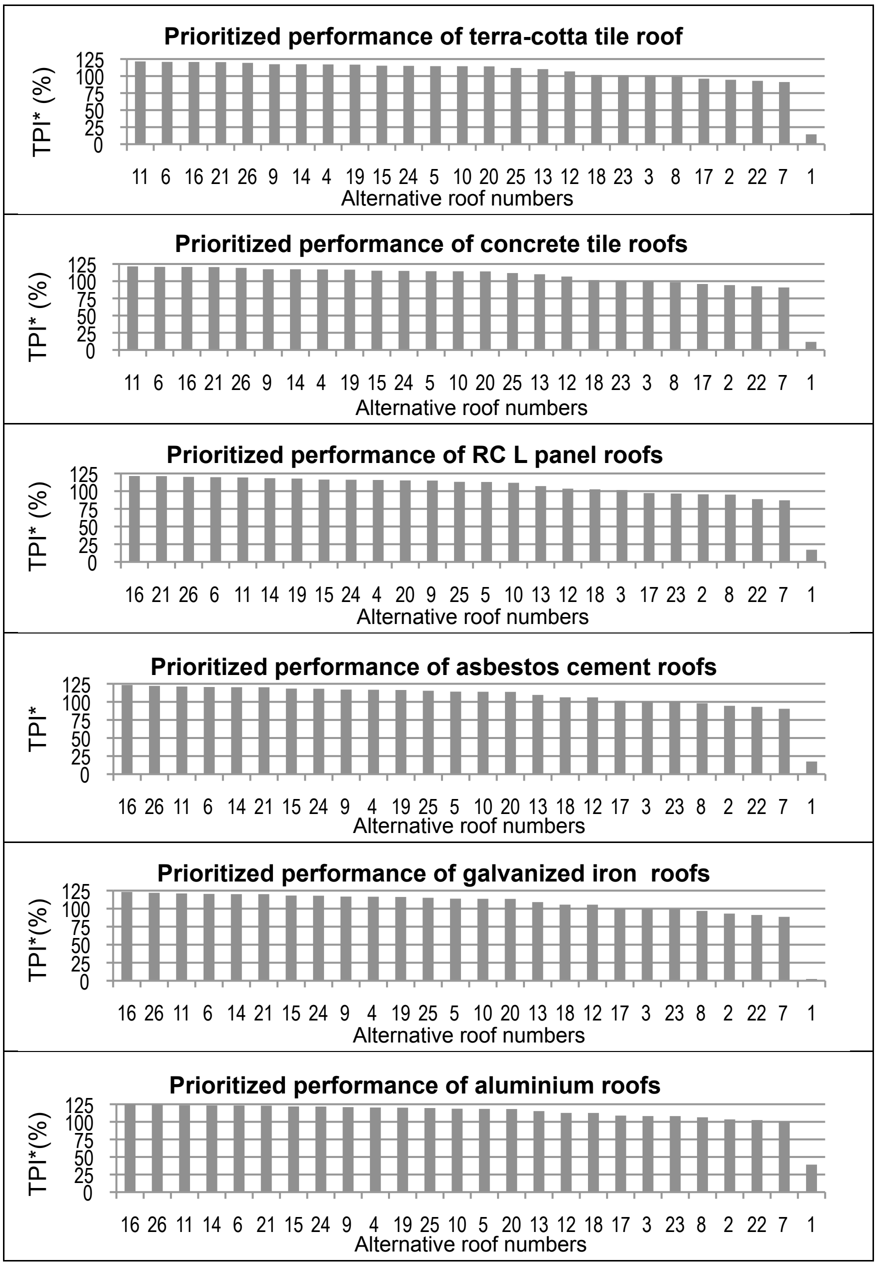

Fig. 5. Prioritized performance (TPI) of alternative roofs in Trivandrum (India).*

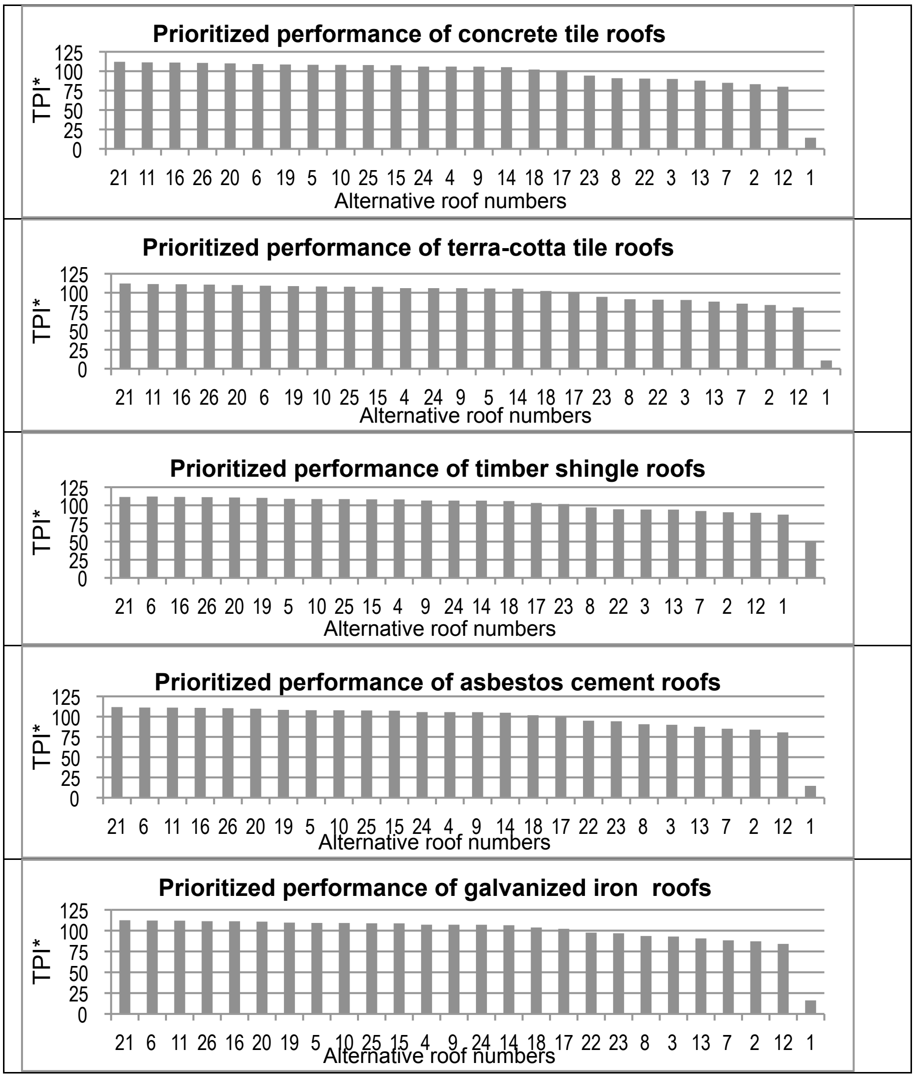

Fig. 6. Prioritized performance (TPI) of alternative roofs in Cairns (Australia).*

For Cairns six cladding materials and five ceiling materials are selected. Table 2 presents thermal performances of one hundred and thirty alternatives during the hottest month of January in Cairns. The performances of Pareto set of solutions are assessed in terms of TPI*. A prioritized ranking of solutions is prepared for each cladding material. The best design for controlling radiant heat gain is found for each of the cladding material and collectively these designs represent the best solution within the Pareto set, Figures 5 and 6.

6. Conclusion

The proposed CAD model for climate responsive roof design, based on generation and optimization, demonstrates that the process is of most benefit to the designer when applied to well-defined problem. The process described has been implemented to handle single objective initially but has the potential to be used to handle multi-criteria problems. It would seem logical that the more information you can apply to the optimization of a computational model, the more useful the result. In fact, because of the nature of the building design process and of the information available to be applied, the opposite is most often true.

Further research is planned to look into more detail at the comparison of results produced by slightly different approaches to the same problem. This includes using a range of starting points in the model generation and different decision making methods, as well as the integration of more complex parameter optimization. The ill-defined information processes would be linked to the proposed model in the collaborative environment involving specialists and knowledge based systems.

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References

1. Mitchell, W.J. (1977). Computer Aided Architectural Design. Van Nostrand Reinhold, New York.
2. Gero, J.S. (1983). Computer aided architectural design — past, present and future. Architectural Science Review 26 (1) : 2–5.
3. Mitchell, W.J. (1994). Three paradigms of computer-aided design. Automation in Construction 3(2-3) : 239-245.
4. Newell, A. & Simon, H.A. (1972). Human Problem Solving. Prentice-Hall.
5. Coyne, R.D., Rosenman, M.A., Radford, A.D., Balachandran, M. & Gero, J.S. (1990). Knowledge-Based Design Systems. Addison Wesley, Reading, Massachusetts.
6. Shaviv, E., Yezioro, A., Capeluto, I.G., Peleg, U.J. & Kalay, Y.E. (1996). Simulations and knowledge-based computer aided architectural design (CAAD) systems for passive and low energy architecture. Energy and Buildings 23 : 257-269.

7. Kalay, Y.E. (1999). The future of CAAD- from computer aided design to computer-aided collaboration. In Kalay, Y.E. (Ed.). Computers in Building : Proceedings of the Eight International Conference on Computer Aided Architectural Design Futures (CAAD Futures) held in Atlanta, Georgia, USA 7-8th June1999, Kluwer Academic Publishers : 13-30.
8. Radford, A.D. & Gero, J.S. (1988). Design by Optimization in Architecture. Building and Construction, Van Nostrand Reinhold, New York.
9. Kabre, C. (2008). Computer aided design of climate responsive dwelling (roofs) in the climatic and technological context of India and Australia. Ph.D. Thesis, Department of Architecture, University of Queensland, Brisbane, Australia.
10. Mitchell, W.J. (1990). The Logic of Architecture : Design, Computation, and Cognition. The MIT Press, Cambridge, Massachusetts.
11. Norton, S. (2010). Construction and generative design, CAD details. http://www.caddetails.com/2004/main.asp?article=Janaury2010.htm.
12. Shea, K., Aish, R. & Gourtovala, M. (2005). Towards integrated performance-driven generative design tools. Automation in Construction : 14.
13. Shaviv, E. (1975). A method for the design of fixed external sun shades. Build International 8 : 121-150.
14. Shaviv, E. (1985). A model for the site layout of solar communities. SunWorld 9(4) : 113-128.
15. Khemlani, L. (1995). GENWIN : A generative computer tool for window design in energy-conscious architecture. Building and Environment 30 (1) : 73-81.
16. Marsh, A. (2004). The optimization of stadium roof glazing for cost and solar access using built form generation based on performance optimized solutions to tightly defined design problems. 21st International conference on Passive and Low Energy Architecture, Eindhoven, 19-22 September : 1016-1022.
17. Goldberg, D.E. (1989). Genetic algorithm in search, optimization and machine learning. Addison Wesley.
18. Cohon, J.L. (1978). Multiobjective Programming and Planning. Academic Press, New York.
19. Radford, A.D. & Gero, J.S. (1988). Design by Optimization in Architecture. Building and Construction, Van Nostrand Reinhold, New York.
20. Marsh, A. (2008). Generative and performative design : a challenging new role for modern architects. The Oxford conference, WIT Press, session keynote.
21. Kabre, C. (2010). A new thermal performance index for dwelling roofs in the warm humid tropics. Building and Environment 45 : 727-738.
22. Thiis-Evensen, T. (1989). Archetypes in Architecture. Oxford University Press.
23. Mahdavi, A. (1993). "Open" simulation environments : a "preference-based" approach. In Flemming U, Wyk S. Van (eds.), Proc. of 5th Int. Conf. CAAD Futures Pittsburgh, 7-10 July 1993, North-Holland, Amsterdam : 195-214.
24. Manning, P. & Mattar, S. (1992). A preliminary to development of expert systems for total design of entire buildings. In Kalay YE (ed.) Evaluating and Predicting Design Performance, Wiley Interscience, New York : 215-238.