Evaluating 'Rules of Thumb' for integrating thermal mass into lightweight construction in Australia

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ABSTRACT: The use of lightweight construction systems is common in Australia. Thermal mass materials can be combined with 'lightweight' domestic timber-framed construction to improve the thermal performance of buildings. This paper examines design advice available to designers called Rules of Thumb. These are useful because designers often do not have the information or finance for detailed thermal modelling, particularly during the initial design stages of the project. The quality of the guidance given is important to effective building operation. The paper therefore investigates current Rules of Thumb for construction and suggests how these rules can be improved. It suggests that a holistic systems approach is needed, climate-by-climate which identifies both the quality (kg/m^2) and location (specific floors, walls, ceilings) of the thermal mass for the specific levels of energy savings and comfort levels. A number of improvements to the existing Rules of Thumb are recommended such as relating them more widely to overall building thermal systems and using rules that augment each other. New rules are suggested for design, which satisfy energy conservation measures now required in practice and by legislation.

Conference themes: Construction technology, Sustainability issues
Keywords: Thermal mass, rules of thumb, thermal comfort

INTRODUCTION

This paper has been prepared as part of a larger project investigating how 'thermal mass' can be combined with 'lightweight' domestic timber-framed construction to create buildings which are thermally comfortable at all times of the year and to minimise active heating or cooling energy. The use of thermal mass is not a solution to thermal comfort in itself but only one system used as part of a holistic design system, which includes insulation, infiltration, ventilation, a pattern of occupancy and other factors. Hence, the difficulty in creating guidance for the use of thermal mass is how it combines with these other parameters to realise the advantages promoted by industry groups. The first paper provides an initial background to the research. The second part discusses the definitions, limitations and scope of using rules of thumb to provide effective guidance. It looks at ways to improve the Rules of Thumb for Thermal Maas. A third part provides ways of improving approximation methods, and considers the value of quantitative rules versus the use of more commonly used qualitative rules. The fourth part considers how qualitative and quantitative rules of thumb can work together and suggest new Rules of Thumbs. This will provide the basis for further research into developing data sets to create new design guidance.

1. BACKGROUND

Many proponents of energy efficient housing recommend high thermal mass as a key element of delivering improved thermal comfort. Manufacturers of high mass building products (e.g. brick, concrete) have shown that introducing mass can, in certain circumstances, deliver a narrowing of internal temperature fluctuations. Lightweight timber-framed construction is viewed as inherently energy inefficient but it is commonly used as a construction system in Australia.

The research questions that remain are as follows:

1. How much thermal mass is needed to improve performance of lightweight houses?
2. Where is it best located within a house?
3. How can it most cost-effectively be built into timber-framed construction to match the level of performance of high mass structures?
4. What are the energy and comfort benefits in terms of current Code requirements?

Addressing these questions is becoming more apparent as more stringent energy efficiency regulations are implemented in each state and territory around Australia. Minimum 6-star thermal comfort regulations have been introduced in Queensland and the ACT in 2010 and Victoria and possibly NSW will follow in 2011. Barriers to achieving these benefits include lack of knowledge of practical applications, lack of basic research about minimal thermal mass needed to improve lightweight buildings and lack of an easy to understand guidance amongst industry representatives and building designers to translate research into project homes and house design. Thermal mass is one strategy in a suite of passive design strategies that that can be used to create low energy buildings. The science underlying these strategies is well researched and available in the literature. There is also an abundance of studies that demonstrate the application of these strategies in practical guidelines. Guidelines are often largely generic and describe the building attributes necessary to introduce passive strategies.

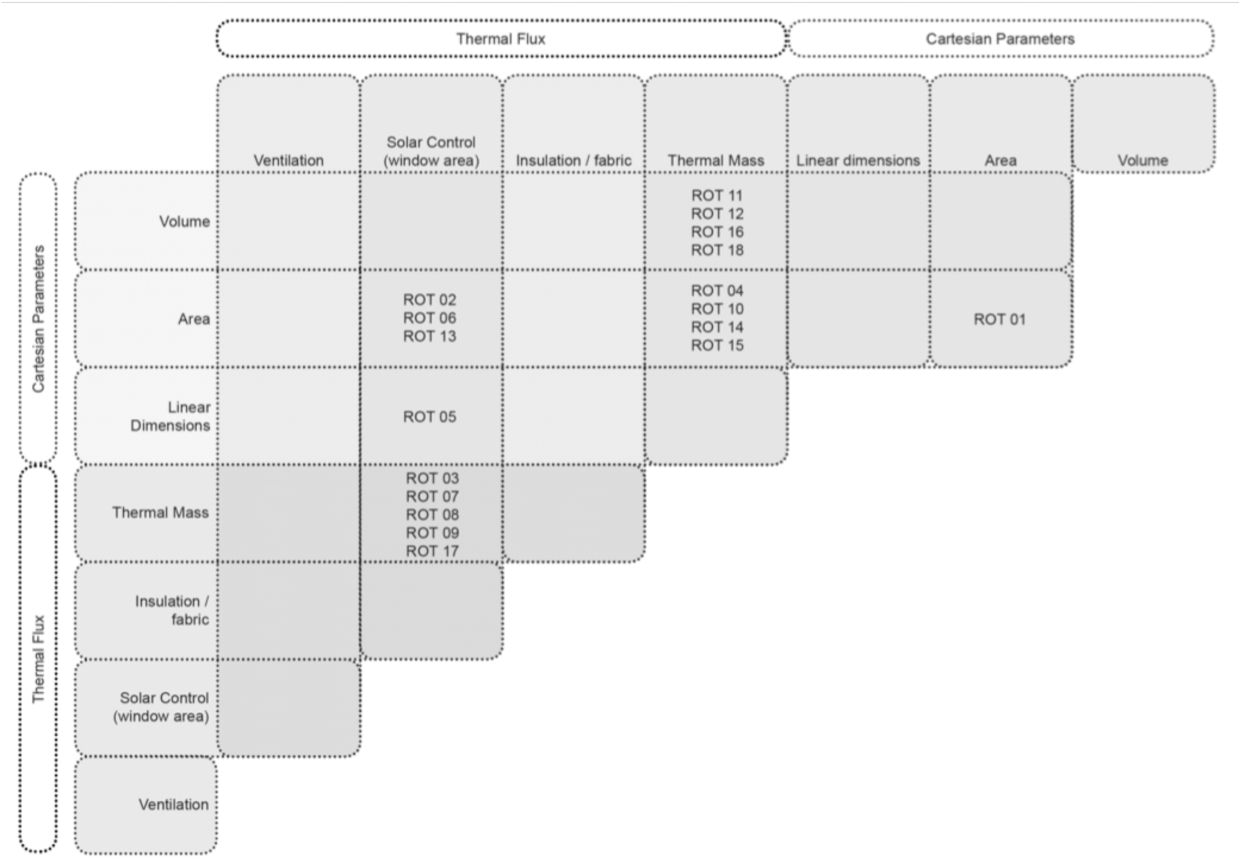

Figure 1: Rules of Thumb tabulated by the parameters (Source Authors)

For example the TRADA (Timber Research and Development Association) manual from the UK on energy efficient housing provides a set of systems necessary to include in housing but without any indication of the likely performance or comfort benefits. Similarly, the current 'Your Home Design Guide' by the Commonwealth of Australia provides advice about the strategies and case studies for different climate types of buildings that have used these strategies. Also, the guide provides an evaluation of case studies which demonstrate the operational performance benefits of the use of the systems used either though simulation or by monitoring (Commonwealth of Australia).

This evidence-based approach is now superseding earlier approaches to design guidance. Work over the last five such as that of the International Energy Agency Task 28 into Sustainable Housing has given methodologies for developing guidelines for houses, which focus on developing rules of thumb for buildings (Hyde et al. 2008). These follow a critical case methodology involving a total system approach. In complex semi-closed systems such as buildings it is hard to identify causes and effects so a total system approach is used. Projects can be created as a set of parametric data, which can be modelled to validate performance benefits. Work in this area by Lukman et al. (Lukman, Hayman and Hyde, 2009) provides a methodology for developing rules of thumb using this kind of parametric computer simulation modelling. Valuable lessons are learned from this approach as to the quantitative aspects of the project, i.e. the amount of thermal mass, the technologies used to deliver this mass effect and so on (Hyde 2000).

A next step would be to examine conventional and innovative building approaches to the use of thermal mass in timber buildings and other technologies to improve energy conservation and comfort. Hence the study would extend previous work by providing detailed quantitative information about the type and location and effects of thermal mass for particular climate types- hot humid, moderate and cool. The work will be based on practice evidence for particular climate types (Hyde 2000). Validation is needed hence an analogue test cell methodology similar to and in conjunction with the work of Dewsbury is proposed (Dewsbury et al. 2009). However, current rules of thumb are largely based on experience and not validated by an experimental approach so this kind of study is critical in providing research evidence to support sound advice to practitioners (Vale and Vale 1975, Oppenheim 2009).

2. RULES OF THUMB FOR THERMAL MASS

2.1 Definitions and limitations

Designers often need quite specific guidance on materials and construction techniques at an early stage of the design process when it is not possible to provide the detailed information required for thermodynamic computer modelling. On smaller (domestic) projects designers often also lack the finances to carry out this modelling at any stage. So designers rely on intuition, qualitative guidance and, occasionally, quantitative rules of thumb. A rule of thumb is defined by the Oxford English Dictionary as '(noun) A particular rule or principle derived from practice or experience; a rough guideline.' It goes on to add '(Adjective) Of a method, procedure,..: derived from practice or experience, rather than theory or scientific knowledge; rough, unscientific' and, 'of a person: working by methods derived from practice or experience; having no recourse to theory or scientific knowledge.'

Stevens describes rules of thumb as 'devices which have worked (or seem to have worked) in the past. They are not based on any sort of theory.' He goes on to state that 'a rule of thumb is useless as an aid to understanding. Since the rule was developed up precisely because there is no theoretical guide' (Stevens, 1988 p223). In an entertainingly titled paper 'On thoughtless rationality (Rules-of-Thumb)' Amitai Etzioni explores the use of and relevance of rules of thumb with particular reference to economics and sociology. In the paper he argues that '(a) the empirical evidence about the rationality of these rules is dubious, and that (b) they cannot serve as a basis for rational conduct. He who lives by rules of thumb may be somewhat less or somewhat more non-rational than those not so guided' (Etzioni 1987). Hence, 'anyone who tried to make fully informed rational choices would make only a handful of decisions each week' (Frank 1987 p3-4) and 'since all real decisions are made under conditions of imperfect information, calculation down to the last decimal place is pointless' (Baumol and Quandt, 1964).

The point here is that 'rules of thumb' are made as a guide to decision making in complex situations and require a level of interpretation. In the context of this paper, the designer may not have the expert knowledge to enter into what could be termed a rational process of calculation of the effects of thermal mass required to identify the thermal environment of a building. Hence a simple approximation will be helpful. Etzioni goes on to identify six limitations with rules of thumb (Etzioni, 1987 pp505– 508), which form a useful bases for identifying a framework for the definition and use of rules of thumb.

Table 1 Limitations guiding the use of Rules of Thumb (Etzioni 1987)

1. *Rules are typically advanced in isolation.* When defining a rule it is important to relate it to the larger system. It is equally important that those using the rule have a qualitative understanding of the large and complex system they are creating by designing a building.
2. *With more than one rule, those rules often conflict with one another.* This is quite possible which is why the issue of understanding is so important. Successful design is the resolution of conflicting rules, requirements and ideas.
3. *Rules are typically formulated as if they were universal truths, applying to all circumstances, times, and people.* Again this is true in general but not true of a useful rule. A rule will only be useful if its limitations are clearly defined.
5. *When rules conflict people will follow the rule that coincides with their subjective estimates and values.* Rules must be used critically as part of an exploration and understanding of a larger and more complex system. In defining, validating and publishing rules we can only offer education.
6. *Rules are often not sufficiently specific to provide guidance (they are ambiguous)..*A useful rule must be specific and based on scientific research or validation (Note Stevens 1988 above).
7. *Rules people follow in their decision-making are used to support rational decision-making however sometime the reverse of this process occurs.*

In summary, the advice for creating Rules are first; the Rules of Thumb must be derived from science and validated through a **scientific (repeatable) process and second; the scope, context and limitations** of the rule must be clearly defined. When using a Rule, it must only be used as part of a broader understanding of the whole system and results derived from calculations must be critically assessed. For example, in the rule to define the depth of floor joists, the rule advocates that the 'Depth of joist = Span/21.' If this were the limit of the information then the rule would fail on every count because there are a number of other considerations about the characteristics of the joists:

1. SC3 grade softwood timber (a structural strength grade);
2. 50mm wide (or more);
3. At 400mm centres;
4. The maximum load on the floor is 1.5KN/m2; and
5. The rule applies to simply supported clear span floors.

The rule is clearly prescriptive and explicit. It is derived from table A1 in the UK building regulations 'Approved Document A (Department of the Enviornament, 1997) which is in turn based on information from TRADA and the British standards, specifically BS 8103-3:1996 Structural design of low-rise buildings, code of Practice for timber floors and roofs for dwellings. Therefore this rule meets each of the criteria set out above however in some case other **implicit** conditions are often ignored. In this case it is assumed the rule is applied by a designer's knowledge of structures and construction. Without this the rule may not be applied intelligently and the results are erroneous an can lead to significant failure in design.

Rule no.	Rule	Description	Reference
Thermal Mass : Volume			
ROT 11	1m^2 mass : 4.5m^3 air	The thickness and density of mass is defined. This rule effectively relates the surface area of mass in a space to its volume.	Baggs & Mortensen 2006 p.5
ROT 12	80kg mass per m^3 air	A development of the rule above using mass rather than an area of a defined mass. It has the advantage of allowing the designer to vary the arrangement of the mass.	Baggs & Mortensen 2006 p.5
ROT 16	Total thermal admittance / Total volume	The ratio needs to be defined for different climates. Total thermal admittance is related to internal surface area of a space being the admittance of each surface added together. This formula creates a ratio between the rate of energy absorption/release in the space and the volume (size) of the space.	Hacker (Slee) 2010
ROT 18	kg mass per m^3 air	The rule tabulates ratios for different climates. Essentially the same as ROT 12 above but providing more detailed parameters.	Baggs & Mortensen 2006 p.4
Thermal Mass : Area			
ROT 04	600 Kg Thermal mass per m2 internal floor area	The advantage of this rule is its simplicity. The disadvantage is that no reference is made to the size (volume) of the space. Hence a low space is allocated the same amount of mass as a very tall space of the same floor area.	Oppenheimer 2008
ROT 10	Kg mass / Floor area > = 0.6	Baggs and Mortensenn derived rules 11 and 12 from this rule. The rule suffers from the disadvantages of ROT 04 above. These three connected rules are perhaps more interesting as an exercise in the best way to represent and a relationship and define it's parameters.	Baverstock 2004
ROT 14	Total heat capacity / Total floor area	Total heat capacity in a space need not necessarily be related to surface area however the way in which the BRE set out the calculation of their thermal mass parameter a relationship is encouraged. The advantage of this rule is that it specifically looks at the energy capacity of the space. The disadvantages are that this is not related to the volumetric scale of the space nor the surface area over which that energy is to be exchanged.	BRE SAP 2009
ROT 15	Total Thermal Admittance / Total floor area	A development of the rule ROT 14 above the ratios for different climates need to be developed through further study and experimentation. This ratio relates thermal capacity to surface area by using thermal admittance or the ability of the surfaces in the space to absorb and release thermal energy.	Hacker (Slee) 2010

Figure 2. Selected rules of thumb that have been analysed as part of the study (Source Authors).

Hence, it is common that rule of thumb applications normally defer to more expert appraisal in this case a structural engineer. The importance of understanding the steps from the application of the approximation to the realisation should acknowledge both the implicit and explicit criteria to evaluate rules of thumb for thermal mass.

2.2. A Review of Existing Rules Relevant to the Use of Thermal Mass

A review of literature on thermal mass, passive solar design, energy efficiency and thermal comfort as well as discussions with experts has identified seventeen Rules of Thumb relating to thermal mass. The first step involved collecting the Rules of Thumb as shown in Figure 1. These have been numbered and grouped according to the parameters that are used to calculate the desired output, namely the amount of thermal mass. It appeared that all rules with the exception of Rule 01 (ROT 01) share a common goal of relating two parameters to each other as a ratio. For example kilograms of thermal mass per square metre of floor area. Furthermore, the Rules appear to fall into two categories. First, thermal flux, these relate amount of thermal flux to the amount of thermal mass as measured by one of the three possible Cartesian parameters and or principally floor area, Second solar control, these relate solar control such as window area to the amount of thermal mass.

The second step was to examine these categories according to the criteria for effective ‘rules of thumb', namely they must be derived from science and validated through a scientific (repeatable) process and the limitations of the rule must be clearly defined. With regard to scientific process, most of these rules meet these criteria to some extent, however it is not always obvious what the scientific process has been used. A similar comment applies to the limitations and context, in particular neither the climate type nor the microclimate conditions are often not clearly stated. For example the rules proposed by Mazria are clearly set out. However when repeated in a more explicit fashion by Sodha the explanation, constraints, climate information and scientific basis of the rules are lost. Mazria is careful to define the Latitudes within which his rules can be used. These are 28^o – 56^o north or south of the equator or equivalent to Rockhampton, Queensland down to Macquarie Island which is approximately 600 miles south of Tasmania; or somewhere from a little south of Cairo, Egypt to Ben Nevis to the north of Glasgow, Scotland. Both of which encompass an enormous range of climates. Oppenheim (2007) states quite explicitly that his rules (ROT 01 – 04) are derived from personal experience and that they "seem to have worked" to quote Stevens. Oppenheim goes on to say that further research is required to validate his proposed rules (see Figure 2).

Furthermore, it was evident that an initial weakness of the current Rules of Thumb is that they do not include more parameters which relate to the **scope, context and limitations** of the Rule, for example in the context of the parameters related to climate responsive design of a building. It can be argued that a designer considers three parameters when deciding on the use of thermal mass, the climate – both at a regional level and a site specific level, form – the scale and proportions of the building and how it is physically arranged and orientated on the site and the fabric – what the building is made of and how those various materials are arranged in the construction (Hyde 2000). Further analysis of the Rules of Thumb reveal that of these responsive design parameters, climate is the most commonly considered context parameter. Clearly with reference to Figure 1 there is scope for further improvement of the Rules of Thumb in terms of both scientific processes, including the application of additional parameters such as ventilation and insulation, which are missing from the existing parameters. Furthermore from Figure 2 it seems that there are many assumptions about the location of thermal mass, and the amount of thermal mass prescribed in a Rule and its location.

2.3 Improving Rules of Thumb for thermal mass

This part builds on the previous critique; it examines what additional scientific processes should be included in the rules, the scope, context and limitations and usefulness of the rules, or types of rule, as related to climate responsive design practice **examining the relationships between climate, form and fabric.** It looks at what opportunities exist for improving the existing rules.

Fabric **-** *expand the definition of thermal mass materials, better quantify thermal mass: energy flux ratio*

The first opportunity for improvement in the existing Rules of Thumb is the definition of thermal mass, prescriptions of the amount needed to affect internal environmental conditions and what building materials can facilitate this process. Thermal mass is a term used to describe a material's ability to absorb, store and release energy. This is a function of the material's specific heat capacity (KJ/kg K), which is a measure of the amount of energy needed to raise 1kg of material by $1^{o}K$. For the building designer it is the proportion of a certain volume of material in relation to the materials volumetric heat capacity (KJ/m^3K) – i.e. the amount of energy required to raise 1 m^3 of material by $1^{o}K$. Also important for a thermal mass is the material's ability to absorb and then release energy: a property called admittance (Szokolay 2008) measured in W/m^2K or the quantity of energy absorbed by 1 m^2 of a surface in one second given a temperature difference of $1^{o}K$. This measure is useful because it relates thermal capacity to time (1 W = 1J/s).

Traditional materials with high thermal mass i.e. high thermal capacity are dense such as brick and concrete. However recent innovation in materials has seen the advent of phase change materials that are lightweight and can have the effect of thermal storage in a similar way to traditional materials. Hence in the use of the nomenclature of materials the qualities of the materials should be defined.

Fabric - relate energy storage and the utilization of the flywheel effect due to the diurnal range of temperature

The second opportunity relates the effect of climate on **energy storage**. Conventionally with traditional materials the thermal flywheel effect created by high capacity materials provides a mechanism for energy storage. In cool climates heat is collected during the day and is stored and released during the night, conversely in warm climates coolth collected at night is released during the day. The function of climate is to drive the flywheel through what is called the diurnal range; that is difference in maximum and minimum diurnal temperature drives the flywheel effect. Moreover with the advent of the integration of active systems such as air-conditioning and mechanical ventilation in houses the term Fabric storage capability has become common. By the harnessing the flywheel effect using active systems rather than the diurnal range, there is a dynamic ability to attenuate the heat and coolth in the service environment. In addition this attenuation process has effects on the overall energy consumption of the energetic system. The extent to which the Rules of Thumb make this issue explicit is unclear and it is an important area for improvement.

Fabric - integrates energy storage with insulation and ventilation techniques

A third opportunity relates to the use of **energy storage in conjunction with other technique** such as insulation and ventilation. As seen in Figure 1, the existing rules of thumb do not take into consideration the effects of these fabric techniques, which are as significant as thermal mass in storing energy in buildings. None of the rules we have found relate mass to insulation or other parts of the fabric of the building. There are various qualitative statements suggesting that insulation should be placed on the external face of any thermal mass. There is also discussion indicating that mass should be dark and matt to maximise the ability of the mass to absorb solar radiation and emit thermal energy (shiny surfaces are poor emitters).

Furthermore ventilation is critical to the successful use or avoidance of overheating in the thermal storage system in a building. While there are a large number of papers exploring the use of natural ventilation and thermal mass, particularly for office buildings, no one appears to have tried to establish simple guidelines for designers to use at an early stage in the design process. A study by Kivva et al. (2009) suggests that rate and method of ventilation is critical because it is the amount of time the air is in contact with the surfaces in the room, which is important. Kivva et al. conclude that allowing ventilation at air speeds greater than 2.5 m/s is counterproductive. Looked at another way these results suggest that mass surface area: volume ratios become important as well as the ability of that mass to exchange heat energy with the air (admittance). The buildings that use labyrinths to temper the temperature of incoming air have used this principle for many years. This issue relates to the way that Fabric storage systems are linked to external energy sources through techniques such as solar gain and ventilation.

Farbic - utilizing a direct gain system

The fourth opportunity relates to how the rules of thumb capture the thermal dynamic process necessary to drive the flywheel approach. Hence the use of active systems described previously can be complemented by passive systems whereby a direct gain system is used to bring heat from solar gain to charge the fabric or external air to heat or cool the fabric of the building. However this requires precision in design, which the rules of thumb seem to be unable to capture. This is of significance when related to solar control, i.e. the sun is excluded in summer through shading systems whilst in winter heat gain is needed and is related to either the floor area or the total surface area of the internal mass to the window area. Unfortunately, the relationship of solar control to the fabric storage (thermal mass – all these rules use surface area) in the Rules of Thumb shown in Figure 2 give no indication of what the solar control is needed for the rules to work. Should the window be fully exposed to the sun at the height of summer? Almost certainly not, however there is no indication of the percentage of window which should be exposed the sun in winter, or shaded in summer. This precision is critical for passive solar heating or cooling. It is very difficult to get right so the designer needs some way to gauge (quantify) the amount of control provided during different parts of the year.

In their current form, with their limited definition of parameters, none of these are helpful because they omit a critical piece of information. Furthermore, the relationship between the amount of energy which enters a space (direct radiation, activity and ventilation), the amount of energy which can be stored in the space (thermal capacitance/thermal mass) and the amount of energy which leaves a space (ventilation and fabric) are critical relationships which must be understood to create thermal comfort. The major fault of the rules described above was their failure to define or control the amount of radiant energy that can enter the building at different times of the year. This is a flaw in all of the rules identified by this paper although it is perhaps less critical for some of the other relationships defined here because they are not dealing explicitly with direct solar radiation. The other rules deal with this relationship through the following assumptions:

- The direct solar radiation into the space will be controlled
- The space is used for domestic activities
- The climate is defined and gains from ventilation will be directly related to the climate

Fabric and form - effects on comfort and indoor environmental quality

A fifth opportunity for improving the use of the rules of thumb is **how thermal mass effects the** sensation of **temperature** within a room. An important part of the environmental quality of internal rooms is the influence of r**adiant heat** from surfaces such as floor, walls, windows and ceilings. These elements will exchange thermal energy with people and other surfaces (including the sun) by radiation. If the surface is at a higher temperature than the surface of our body, so we are receiving radiant energy from it, then it will feel warm. If it is at a lower temperature, so we are losing radiant energy to it, it will feel cool. **Furthermore**, the surfaces are in contact with the air in the room and constantly exchanging thermal energy with the air through convection. If the air is warmer than the surface of the mass, then the mass will absorb thermal energy from the air, cooling the air down. Occupants of the room will experience a lower ambient temperature. If the surface temperature of the mass is higher than the air, for example in the evening, then the mass will warm the air, which will circulate (convection) so the ambient temperature will be increased. If we touch (stand on, sit on etc.) a surface which is cooler than our own thermal energy will be conducted away from us into the surface, particularly if the material is a good conductor (and dense materials are) and so the part of our body in contact with the cool surface will feel cool. If the temperature difference is reversed we will feel warmth. As a result of this it can be argued that where the energy storage system is created though using particular elements within the building, the adjacency of these elements is crucial to the indoor environmental quality visa a vis the experience of comfort for occupants. Hence, where the condition are met for the first five Rules of Thumb are met, then the issues of the location of these elements can be considered. In this case Rules for the location of the energy storage systems in relation to elements such as wall floors and ceilings is important. The existing Rules fail to relate to some of these controlling parameters in a wider systems context as seen in the first limitation in Table 1.

Form and thermal mass

The sixth opportunity is to relate the amount of mass in a space to the floor area, surface area or volume of the space. These rules of thumb describe the mass using units of mass (kg), capacitance (KJ/m^3K) and admittance (W/m^2K). This group of rules are generally clearly defined although some of them require development. The major failing of this group of rules is that solar control is not part of the rule or part of the parameters, which define the use of the rule. It is not even clear that the rule is intended to work with direct solar gain or whether they are intended to be passive (not passive-solar) spaces. Figure 2 provides a brief assessment of each of these eight rules.

Form - volume, orientation and proportions of rooms

Finally there is an opportunity to examine the volume, orientation and proportions of rooms and to assess the impact of thermal mass on thermal performance. High rooms allow for a greater stratification of warmer and cooler air for instance. The orientation of a room relative to the sun and the influence of the microclimate and local landscape are important mediators of thermal performance. These are often described by ‘good practice’ or qualitative rules of thumb but are not included in the quantitative evaluations. This raises important issues and concerns as to how the qualitative and quantitative rules might overlap and work together.

3 NEW RULES OF THUMB

The Rules of Thumb for that apply to thermal mass in buildings is an approximation method which share a common goal of relating two parameters to each other as a ratio for calculating the amount of thermal mass needed in a particular room or building. For example the Rules allow calculation of kilograms of thermal mass per square metre of floor area. Furthermore, the Rules appear to fall into two categories, those using thermal flux and those using solar control, to determine the quantity of thermal mass. Looking closely at the current Rules of Thumb some limitations are found with this approach in terms of the scientific process used to create the ratios and limitations in the scope, scale and context for the rules. Moreover the rules appear to be isolated and not related to the overall system in which they are grounded. To address these problems a number of opportunities are identified for improving the Rules of Thumb based on the work of Etzioni (1987).

Table 2 Possible New Rules of Thumb for Lightweight buildings (Source Authors)

Type	Parameters used on the Rules	Outcomes
Qualitative: Types of thermal mass materials - selection of a base line material such as concrete to compare with other materials.	Units of mass (kg), capacitance (KJ/m^3K,), surface area (m^2) and admittance (W/m^2K).	Thermal mass efficiency i.e. more thermal capacity the more efficient these systems are in theory.
Quantitative: Fabric storage sizing based for base-line thermal mass material, for area of house, for climate location.	Area rules for of base line material- thermal mass type (kg/m2) per area of floor area for admittance (correction factors for other materials)	Capacity of energy storage system for houses and energy efficiency improvements, influence on Star Rating for climate location
Qualitative Quantitative: Improvements in effectiveness of Fabric storage through integration of direct gain system, heating and ventilation effects	Direct gain Index of climate types - an index will be developed for different climates- high directs gain climates will have a high index.	Rating the effectiveness of Fabric storage systems due to integration of direct gain system,
Qualitative: Improvements in effectiveness of Fabric for climate types with diurnal range	Diurnal range Index of climate types. an index will be developed for different climates- high diurnal range climates will have a high index.	Rating the effectiveness of Fabric storage systems due to diurnal range
Quantitative: Fabric storage location for thermal comfort	Location of Fabric storage systems related to occupancy- floors or walls or Ceilings. Temperature in free running mode. Performance improvements per climate.	Capacity of energy storage system for houses and energy efficiency improvements, influence on Star Rating for location, temperature variations for free running operation

First, the Rules of Thumb should be related to the wider systems level. Hence it is recommended to expand the definition and types of thermal mass materials used in the rule, better quantity thermal mass: energy flux ratio and its relation to energy use and temperature. Second, the Rules should be developed so that they augment each other, rather than conflict with one another. Hence rules will be needed to relate the energy storage capacity of the thermal mass to effectively utilize the flywheel effect due to the diurnal range of temperature. In addition it is necessary to have rules, which integrate energy storage effects with insulation and ventilation techniques to improve efficiency of the storage system. Third, whilst the previously mentioned rules are likely to be quantitative, these rules are often not sufficiently specific to provide guidance. Hence is a recommendation to develop a rule that utilizes a direct gain system, this is likely to be both quantitative and qualitative provide the level of specificity for adequate guidance. Fourth, rules are typically formulated as if they were universal truths, however this can be ambiguous. In any specific case it is important to develop guidance for the location of thermal mass to address effects on comfort and indoor environmental quality. This is highly ambitious and will be difficult to achieve except by showing the temperature effects and specific locations of the elements for creating comfort. Proxies for thermal comfort will need to be developed based on the location of thermal mass and likely surface temperature of the surrounding elements. Finally **when rules conflict, people will follow the rule that coincides with their subjective estimates and values**. **Rules people follow in their decision-making are used to support rational decision-making however sometime the reverse of this process occurs.** Therefore, it is necessary to determine the amount of thermal mass required for a particular flux levels in a climate, hence must be understood within a context. The rules of thumb are not a substitute for a detailed understanding of the multiple factors which affect the comfort of a rooms and nor are they a substitute for detailed computer modelling. In fact rules of thumb can only used within the context of a detailed understanding of thermal comfort in buildings. They are tools, which, like all tools, rely on the skill of the people using them to become useful. Used well they can contribute to the design of more comfortable buildings. All tools come with instruction and so we propose that any quantitative rules, which might be created from this research, would fit within a framework of qualitative guidelines or ‘rules of thumb.’ This is part of what was earlier described as defining the limitations of a rule. These qualitative guidelines are generally well known even if they are not well understood or applied by many, they would be regarded simply as good practice by many others.

For a quantitative rule of thumb to be useful in the context of designing and constructing buildings the data needs to be readily available and the calculations easy to make. Thermal capacitance (derived from specific heat capacity) and admittance are not the most readily available properties of materials in most offices so are not the most appropriate parameters to be using in a rule of thumb designed for general use. Mass (kg) or density (kg/m^3) of thermal mass in a room might be a useful proxy for this scientific process. Detailed computer modelling of spaces of different sizes and in different climates as well as measurements from analogue test cells and buildings in different climates will be carried out as the next stage of this project to see if this reasoning is correct, identify the proportions which will work in different climates and to improve the rules of thumb. The suggested new Rules of Thumb are shown in Table 2. These will be based on a typical stock house that is commonly used as a project home in Australia.

CONCLUSIONS

The 2010 round of 'Build tight, ventilate right' seminars by the RIBA in the UK has helped to conceptualise the techniques for achieving a Low Carbon building. The RIBA argues that while the techniques are well documented, the standards are often not achieved in practice through lack of understanding about what makes a highly insulated, airtight and energy efficient building (RIBA 2010). The 'Build tight, ventilate right' approach has straightforward building techniques to show what can be achieved and also what can be done on site to improve building quality underpinned by clear principles and rules of thumb. The approach is part of a broader initiative to building Carbon Neutral or Near Carbon Neutral in the future (Pritchard & Willars 2010).

However, in Australia for many years it has been a case of 'she'll be right, keep it light' with a heavy emphasis on leaky lightweight buildings with poor insulation and inadequate ventilation. A review of the available rules reveals a number of opportunities for improvement of the building stock either through design of new build or retrofitting. The new Rules of Thumb are proposed to improve lightweight buildings. The Rules of Thumb proposed start by **defining types of thermal mass** and then look at a **calculator for sizing a fabric storage system** utilising these types of materials. Further rules are developed which then demonstrate how the fabric storage system can be made more efficient and effective through using climate effects such as diurnal range and adopting a direct gain system. Finally the **rules give guidance for the location of the fabric storage system**, whether floors, walls or ceilings and the influence on temperature and thermal comfort when buildings are in free running mode. Through the modelling of the Rules of Thumb using simulating tools it has been possible to demonstrate the impact on the potential Energy rating of a building, its thermal comfort and its Carbon Footprint (Slee, Upadhay, Parkinson, Hyde forthcoming 2012). In this way, the Rules of Thumb are conceptualised as a cascade so they interconnect and provide effective guidance across a wider set of design issues.

ACKNOWLEDGMENTS

Forest and Wood Products Association, Derek Munn, CSR and Tom Parkinson.

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