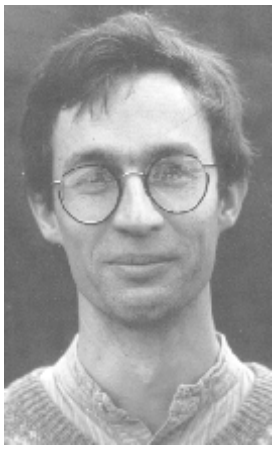
Furniture in Warm and Humid Climates

by Lars Wadsö



Lars Wadsö was born in Sweden in 1961. He earned the degree Master of Science in Engineering Physics in 1986 and the degree Doctor of Science in Engineering in 1993 with a study of water vapour transport and sorption in wood. He is a researcher in the Division of Building Materials, Lund University, studying the moisture properties of building materials and calorimetric (thermal) measurements of processes in building materials. He also works as a consultant for industry.

In his leisure time he gardens and does woodwork.

Contents

1 Introduction

Problem

Poor durability is common with wooden cabinets and other furniture in hot and humid climates. Frequently veneer and plastic sheet laminates loosen after a short time because of the climate. The combination of high indoor temperature and high relative humidity causes rapid deterioration of glues and surface finishes. This deterioration leads to unhygienic conditions, for example when dirt collects under plastic sheet laminates that have loosened from top surfaces. The problem is particularly serious in institutional buildings such as health clinics and schools.

Occasionally it is necessary to import "high quality" furniture to equip institutional buildings or staff housing. It is remarkable that this expensive furniture often has lower durability with respect to the climate than locally manufactured wooden products.

There does not seem to be any general consensus on how to design furniture for very humid climates; advice is very contradictory, such as "use only solid wood" and "use only modern board materials." None of the furniture producers contacted for this study seemed to produce furniture for use in warm humid climates, although many of them had exported their products to hotels and embassies in countries with this kind of climate.

This study is mainly limited to furniture and fittings based on wood and wood products. It concentrates on products made in temperate regions (e.g. Europe) for export to tropical humid or composite climates, but should be relevant for anyone working with furniture for humid conditions.

Mould, rot and termites are only superficially treated here (see Mossberg 1990 and Berry 1993). It is not common to treat furniture with fungicides or insecticides at production, but it is common to fumigate furniture under attack from termites. Wood materials such as boards are sometimes treated with preservatives (see Berry et al. 1995).

The relationship between outdoor and indoor climate (building technique) is not treated here (see Koenigsberger et al. 1974 and de Waal 1993), but in tropical climates it can often be assumed that the indoor climate is as humid as the outdoor climate, whether air-conditioning is used or not.

Standard test procedures for materials are mentioned only briefly. Most such tests concern the behaviour of products in temperate climates. A material classed as "exterior" in Europe may not last in a constantly humid and warm environment.

Brand names are not given as many are local. Materials should be identified primarily by their composition (e.g. a phenolic adhesive), and their properties (e.g. durability) should be guaranteed by the manufacturer.

This report does not discuss the economic aspects of different types of furniture materials and design. This is a difficult subject as the cost of a certain type of furniture is probably more related to the volume it is produced in, than to the quality of the materials used.

Throughout this report "Europe" is used as an example of a region with relatively cool (temperate) climate. Other regions with similar climates are the northern USA, Canada, northern Russia, and northern Japan. Locations with warm and humid climates (the main concern of this report) are called "tropical" or "warm and humid."

The general aim is to give advice for cabinets and furniture in warm and humid environments, such as tropical climates, greenhouses and wet laboratories. A specific objective of this study is to describe the quality requirements for furniture to assure good durability in warm and humid climates. The target group is those responsible for production and tendering of furniture for use in such climates.

Using normal European furniture as a starting point, this study proposes improvements in materials and design. It also gives a general description of the properties of relevant materials.

Method

This is mainly a desk study. The problem was discussed with material and furniture manufacturers, and material specialists, and relevant literature was studied. A small experimental study was conducted of how furniture materials behave at high humidities (Wadsö 1995).

Organization of the report

The report is divided into two parts. The first part, Chapters 1 – 3, contain general considerations and recommendations concerning materials, design and tendering. The second part, Chapter 4, describes furniture construction in a number of case studies. The report ends with a glossary and a reference list.

2 General considerations

Quality and service life

Furniture for warm and humid conditions should have the qualities of good European furniture, plus the ability to withstand prolonged exposure to humid conditions. This report mainly concerns materials and designs to achieve the latter.

The service life can be defined as the time period when the properties of the furniture are acceptable. Furniture in warm and humid climates can generally be expected to have short service lives compared to furniture used in Europe. With the advice given in this report, it is hoped that one shall avoid getting furniture with only a few years of service life, although it is not possible to state exactly how long a service life one can expect from a certain piece of furniture.

When tendering furniture it is important to know the kind of climate the furniture will have to withstand. If the furniture is going to be used in a country with a tropical climate, but in a high-class hotel with constant air conditioning, any type of furniture may be used (although transport from Europe is problematic). On the other hand, if the furniture is to be exposed to the exterior climatic conditions (or even more humid climates, such as a kitchen), the furniture should be made more durable.

Furniture that is expensive and high quality in Europe may not be more suitable for a warm humid climate than mass produced inexpensive furniture. High quality can mean many things. Some of these, such as a famous brand, exclusive woods, and elaborate design, are not likely to make furniture more durable in the tropics. Good workmanship, careful choice of materials, and an interest in the problem of furniture under extreme conditions, are, however, qualities that should be sought.

Furniture that can withstand humid conditions may be expensive, but still economical in the long run. It is costly (administration, transportation etc.) to replace furniture that was not good enough.

Unprejudiced choice of furniture

This report mainly concerns the type of furniture that is produced and used in Europe, but a few words must be said about other solutions to furniture problems in warm and humid climates. Buying a piece of furniture in Europe for export to warm and humid conditions in Vietnam or Brazil is not trivial and may be expensive if it is to have a good service life. It is therefore wise to think of other solutions to the problem: use other materials and designs, use unconventional or low technology solutions. Here are a few examples:

- Instead of using a stainless steel kitchen sink and a separate work bench of board material, make the whole construction of stainless steel. Almost all types of furniture are produced in stainless steel, although only the sinks may be affordable.
- Concrete is a durable material. Stationary furniture (chairs, benches, tables, wash benches) in concrete may look clumsy, but will function well in many applications (Pudeck and Stillefors 1991).
- Use locally available materials. Pudeck and Stillefors (1993) show how simple school furniture may be constructed from adobe.
- Must all the furniture in one place look alike? Furniture can be bought piece by piece at the local market. A major problem for local producers is that they are often so small that it will take a long time for them to produce the furniture needed to furnish an office or a school.
- Does the finish have to be high? Does a work bench have to be board-flat and glossy? Buildings for development purposes do not have to be furnished in latest style in Europe. Note also that high finishes often deteriorate quickly in warm and humid climates.
- Exterior plywood is a very tough material (especially phenolic film faced varieties which are used in concrete formwork and in exterior playground equipment) that could be used for all types of furniture.
- It is probably safe to assume that most outdoor furniture used in temperate climates will serve quite well *indoors* in tropical climates.
- In warm humid climates one should avoid unventilated wardrobes, cupboards and drawers. It is much better to have open or ventilated constructions that allow moisture in textiles and other materials to dry out. Use doors with louvers or screens, or have no doors at all.
- Rattan furniture is ideally suited to conditions of varying or high humidity.

Climate

The single most important climatic parameter for indoor furniture is the relative humidity (RH), as this determines the moisture movements of wood and wood based materials. It is possible to find places on earth with nearly every possible RH variation. The most common climatic classifications are based on meteorological observations or on the vegetation. These are generally of limited use in connection with furniture. There are, however, a few simplified classifications by building scientists (e.g. Spence and Cook 1983) that can be of some use. Here is a very simple classification into humid and composite climates.

In *warm humid climates* the relative humidity is high (70 – 100%) all year. Such climates are found in places like Colombo (Sri Lanka), Hanoi (Vietnam), Jakarta (Indonesia), Lagos (Nigeria), Mombasa (Kenya), Singapore, and Manaus (Brazil). Furniture in warm humid climates should be made of materials and construction techniques that can endure high humidities and temperatures. Only moisture proof materials should be used, as all parts of furniture in such a climate will experience constant high moisture. If the furniture is produced at a low

moisture in a temperate climate, it has to withstand a large one-time increase in moisture content (and swelling).

In *composite climates* there is a very humid season (rain period) with high relative humidities. The rest of the year is drier, in some cases much drier. Some examples of cities with composite climates are Asuncion (Paraguay), Lahore (Pakistan), and New Delhi (India). The main problem with the composite climate is the variation in relative humidity causing furniture components to have large annual swelling and shrinkage. Furniture for composite climates should be designed so that such shrinkage and swelling of the individual parts will not damage the whole piece of furniture. Coatings (e.g. laminates and some lacquers) can also effectively decrease the amplitude of the moisture movements in climates with large annual humidity variations.

RH-data for different locations may be found in Landsberg (1969–1984) and Pearce and Smith (1990). The values are given either as monthly mean RH, or as monthly mean RH at one or two definite times of the day (usually early in the morning and at noon, when RH is at maximum or minimum). From monthly mean values it is possible to calculate the moisture content variations of thick or coated components of wood and wood based materials. The maximum and minimum RH give the daily variations which can be used as an indication of the moisture content variations of uncoated veneers and thin surface layers.

A few things should be noted about climatic RH data:

- The monthly mean values are higher than the mean of the max and min values (about 5% in a few cases checked by the author).
- The mean values of RH should be used with caution as any one or two years might be drier or more humid than the average over long periods.

Figure 1 shows the maximum and minimum RH for four locations. It is seen that Nairobi has very large daily RH variations, whereas Ouagadougou has extremely large annual RH variations. Figure 2 shows the mean monthly RH in four other places in the tropics. Here, two climates have very high, but stable, RH. The two others are not as humid, but have larger annual variations in RH.

Figure 2 also shows a typical indoor RH in Stockholm. In Stockholm the temperature is very much lower than in the tropical zone and all buildings are heated. As a consequence the RH will be very low during the winter (even if it is about 90% outside). In the tropics the climatic situation is very different. The warm climate makes heating unnecessary and the houses are often open to increase the ventilation. The indoor RH will then follow the outdoor RH, and furniture will be exposed to the outdoor climate, without rain.

A number of factors modify this argument. As the temperature indoors is often higher than outdoors, the

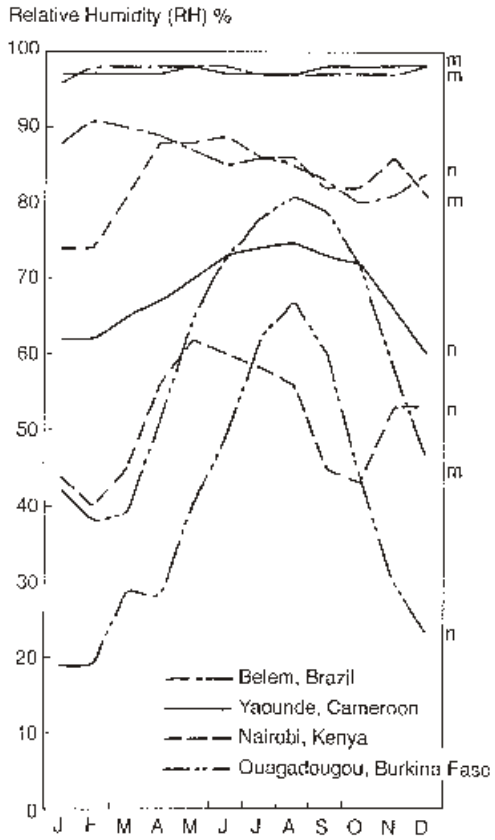


Fig. 1 Daily mean morning and noon RH, over a year, in four tropical climates. The RH is higher in the morning (around 7.00) (m) than at noon (n).

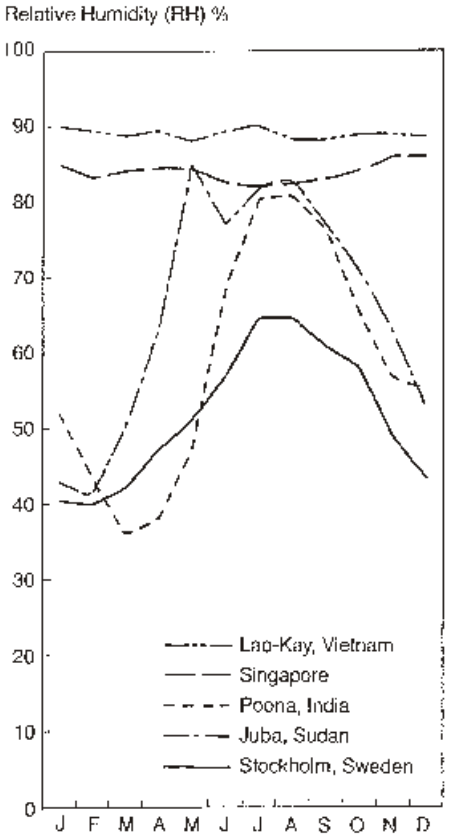


Fig. 2 Monthly mean indoor RH in four tropical and one temperate location. For the tropical climates the indoor RH has been assumed to equal the outdoor RH; for Stockholm the outdoor RH has been converted into an indoor RH at 20°C with a normal humidity input from indoor activities such as cooking.

indoor RH is often a few percent lower than the outdoor RH. Wet activities such as cooking, washing and cleaning, however, raise the RH. In buildings with constant air-conditioning, the RH may be lower, but air-conditioning often lowers only the temperature, not the RH. The indoor climate of air-conditioned houses is discussed by Adamson and Åberg (1993).

Temperature is the second most important climatic factor after RH. Higher temperature gives higher rates of all processes such as adsorption and swelling, corrosion, and fungal growth.

Moisture and materials

Moisture is the root of most problems with furniture in humid climates. Here is an introduction to some basic concepts concerning moisture and materials.

Relative humidity (RH) is a measure of the humidity of air expressed in per cent (%). The relative humidity is a useful quantity, as it is used to relate the moisture state of the air to the moisture state of wood and other materials.

Materials such as wood absorb water vapour directly from the air. The amount of moisture absorbed by a material may be expressed as *moisture content (MC):* the weight of the absorbed water divided by the weight of the oven-dry material. It is often expressed in per cent (%). If 40 kg dry wood absorbs 4 kg of water it has a MC of 10%.

When a material is stored for a long time at a constant RH it will reach an equilibrium MC which is related to the RH. Figure 3 shows a diagram of the equilibrium MC of wood as a function of the RH. Such a diagram is usually called a *sorption isotherm*. Note that it is only true when the material has had time to come to equilibrium with a certain RH (Skaar 1988, Hoadley 1994). Measurements and calculations of equilibrium moisture contents are fairly simple.

At near 100% RH the MC of wood based products is about 30%. If a wood based material is exposed to liquid water (e.g. during cleaning, rain or condensation) more water may be absorbed in the pores of the wood fibres, and the MC may rise well above 30%.

When a material absorbs or desorbs moisture to adjust its MC to the equilibrium MC of the sorption isotherm (Fig. 3) corresponding to the ambient RH, the water must be transported through the material. When there is no liquid water present, the transport is by *vapour diffusion*. The ease by which water vapour diffuses through a material is given by its diffusion coefficient, which is a measurable material property. Layers of materials (e.g. coatings) impede moisture transport (moisture resistances). Both diffusion coefficients and moisture resistances are generally dependent on both temperature and MC (or RH). Liquid water can also be transported into porous materials by *capillary action*. Both measurements and calculations of moisture transport are complex.

The absorption of moisture affects a number of material properties. Most important here is the *swelling* when wood and wood products absorb water (and *shrinkage* when the water is desorbed). The swelling is roughly proportional to the amount of absorbed water (up to a moisture content of 30% for wood). This is shown in Fig. 4. Wood and wood based materials have different swelling in different directions. The swelling values given are always values of free swelling; when the swelling of a material is restricted (by other materials in a structure) the swelling will be less, but the material will instead be under stress.

Swelling of wood is normally reversible, i.e. the wood will shrink back to its original size if it is dried. There may, however, also be irreversible changes of form and shape. These are caused by various factors.

- If restricted swelling causes the stress to exceed the strength of the wood, the wood will be compressed beyond its elastic limit so that it cannot recover its original shape if allowed to dry and shrink. This phenomenon is called “compression set” and is a common cause of loose joints in wood furniture.
- Internal stresses in the wood that may be released at high moisture contents when the wood is “weaker.” The stresses may be caused by asymmetrical growth

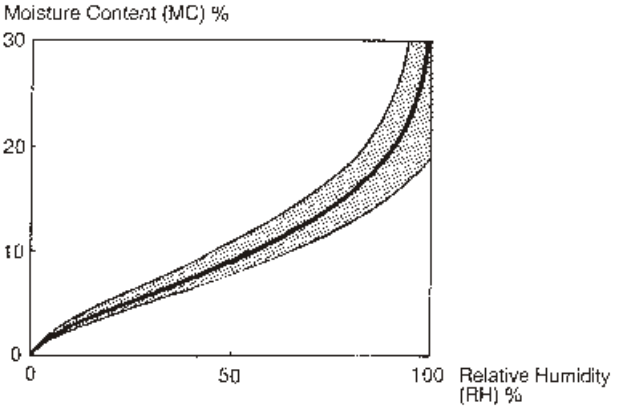


Fig. 3 A sorption isotherm showing the relationship between relative humidity and equilibrium moisture content of wood. The shaded area includes different species and sorption conditions. Most woods have isotherms close to the mean curve.

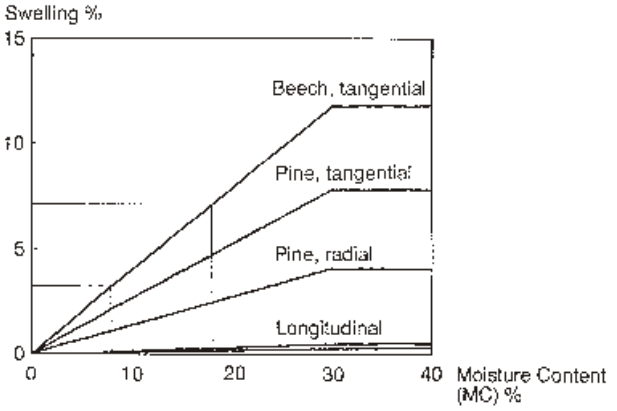


Fig. 4 The swelling of dry wood. The swelling between two arbitrary moisture contents can be found as the difference between the swelling of dry wood to these moisture contents (For example, the figure shows that swelling is about 4% when moisture content increases from 8 to 18%).

of the tree, the drying procedure, or the way the furniture was produced (e.g. by bending).

· Interior quality board materials also show irreversible swelling behaviour at high RH. This is caused by the breakdown of the adhesive they are produced with.

Wood materials loose *strength* and *rigidity* when they absorb water vapour. As an example, the compressive strength of dry wood parallel to its fibres decreases by 2/3 when the wood obtains a moisture content of 30%.

Creep is the increased deformation with time of materials under stress. This phenomenon is most readily seen in bookshelves which, after a few years under load, will sag noticeably. Generally,

– increased temperature and humidity gives increased creep;
– variations in MC also increase creep.

Corrosion of metals should also be mentioned here, as it is accelerated by high RH and the presence of air borne pollutants and sea salt.

The moisture content of wood in use

Furniture should preferably be produced with the mean moisture content of the climate where it will be used, as this will minimize the moisture movements. The main problem with moisture in the wood working industries of Europe and the USA has been *to dry* the wood to the appropriate mean moisture content. It is well known that a single piece of wood with too high moisture content can ruin the appearance of the furniture. The problem treated here is the opposite: which kind of furniture produced at low moisture content can serve in a more humid climate? A number of reports concerning issues in Europe and the USA are, however, interesting also for those concerned with tropical climates (e.g. Forest Products Laboratory 1957, River and Okkonen 1991, Hoadley 1994).

The upper part of the following table shows the mean moisture contents (in %) recommended for six temperate locations:

England	11
Japan	11
USA (Nevada/Utah)	6
USA (West Coast)	11
New Zealand	12
Sweden	8
Amazonia	20
Singapore	18

The table also shows the calculated mean moisture contents in two very humid locations. Furniture produced for the European market will have to absorb a lot of moisture to come into equilibrium with such humid climates. Figure 5 shows the moisture content of thin uncoated wood boards in three indoor climates. It can be seen that in the very humid Vietnamese climate, wood will be at a constant high MC. The two other climates are more variable. In the composite Indian climate, the MC variations will be about twice those in Stockholm.

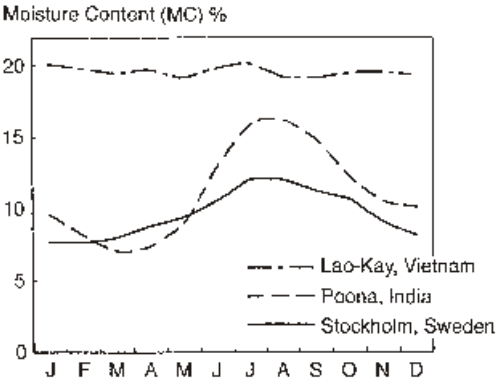


Fig. 5 The moisture content of wood in equilibrium with three of the climates given in Fig. 2.

Failure to control the moisture content of the timber used in furniture sufficiently well will cause the finished product to warp or split when it is exposed to the atmospheric conditions in foreign markets. Many tropical developing countries are beginning to appreciate the importance of seasoning and are installing kiln-drying and humidity control equipment. The same line of reasoning could apply when furniture is exported from temperate to tropical climates: the manufacture should take place at the mean MC of the destination of the furniture. This is, however, usually not possible as the export from temperate to tropical countries is marginal, and the production plants are built for low moisture contents.

The moisture content of wooden furniture is a function of the RH, the sorption isotherm (Fig. 3), and the dimensions and coatings of the wood. Figure 6 gives the typical annual RH variations during a three year period in three locations with different tropical climates. Figures 7a–7c give calculated mean moisture contents of three furniture components placed in these climates; their original MC was 8% (Wadsö 1994).

a An uncoated softwood board 20 mm thick (a thinner uncoated piece of wood, e.g. a veneer, will show a very similar result)

b An uncoated softwood board 100 mm thick

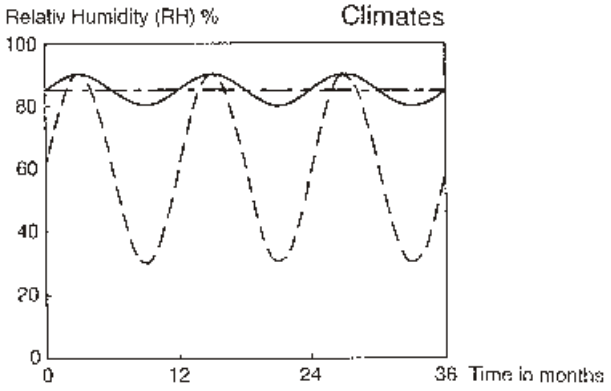


Fig. 6 Three idealized climates used in the calculations for Figs. 7a–7c.

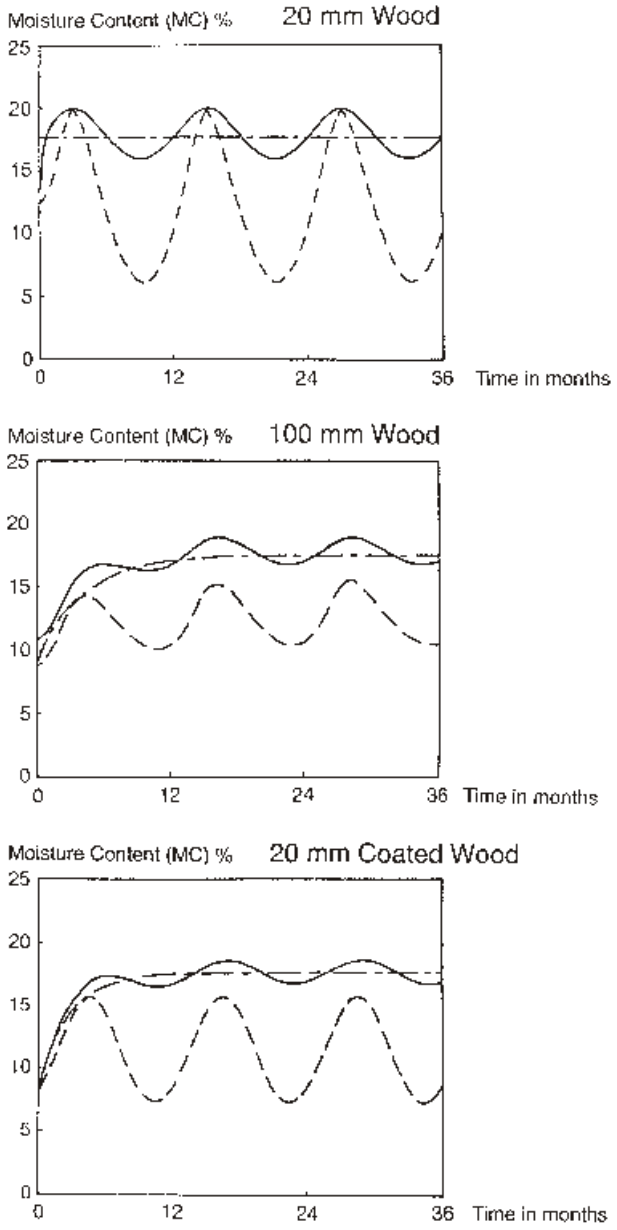


Fig. 7 The moisture content of three wood components (described in the text) exposed to the climates given in Fig. 6.

c A 20 mm thick softwood board with a vapour-tight polyurethane coating.

The following conclusions may be drawn from these calculations:

- Thin pieces of uncoated wood will closely follow the mean monthly variations in RH (a thin uncoated veneer would also follow daily RH variations closely).
- In composite climates a thicker material has less MC variations than a thinner piece.
- In a climate with a constantly high RH, even thick or coated wood components will reach high moisture contents in equilibrium with the ambient conditions in less than a year. However, in climates with varying RH, coatings may reduce the fluctuations in moisture content (and therefore the swelling and shrinkage).

3 Recommendations

This section concentrates on the properties of furniture materials. The part discussing furniture design is short, but the information given concerning the materials' properties is also relevant for the design of furniture.

Materials

The advice given here is quite general. It is impossible to cover the hundreds of wood species or thousands of glues and coatings used in furniture making. It is important, especially when it concerns chemical products, to seek the advice of the manufacturers. Products that look alike may have very different durability under humid conditions.

Wood

Wood is an excellent material for furniture and fittings. It is light and strong; it is easy to work with and feels good to touch in both warm and cold climates. The main problems with wood all have to do with its ability to absorb water vapour from the air.

Different woods have different properties. Some examples of properties that are important for furniture manufacturing for warm and humid climates are given here. For details on individual timbers there are several handbooks available, e.g. Farmer (1972, 1977) and BRE (1984).

Wood has three main structural directions: longitudinal, tangential and radial (see Fig. 8). The tangential and radial directions are often called the transversal directions. All wood properties have different values in these three directions, but the two transversal directions often show quite similar values. Of interest here is that the swelling in the longitudinal direction is much lower than the swelling in the other directions. Different woods have different swelling. Here are some typical values (% swelling when moisture content increases from 0 to 30%, see Fig. 5):

Swelling	*Long.*	*Tang.*	*Rad.*	*Examples*
high	0.4	11	5	beech, ramin
medium	0.4	8	4	pine, spruce
low	0.4	4	3	teak

The tropical timber teak is a very good with respect to moisture movements. There is, however, no general rule

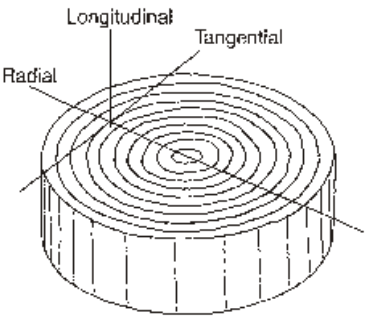


Fig. 8 Directions in wood.

that tropical timbers have lower swelling than timbers from the temperate zones.

When wood with sharp growth rings (e.g. pine and spruce) swell, the wood surface may assume the shape of a washboard. This is caused by the different swelling-properties of the early and late wood parts of the growth rings. Such surface unevenness may be visible through laminates and veneers. (This phenomenon is called "telegraphing.")

Wood and wood based materials can be attacked by mould, rot and insects. Above 75% RH there is always a risk of mould and stain growth on surfaces of wood and other materials. These fungi do not digest the wood and therefore cause no loss of strength. At very high RH or under exposure to water, rot fungi can attack wood materials. Rot fungi digest the wood causing destruction of building components and furniture. Similarly, insects like termites also destroy wood objects.

The natural protection in wood to fungal and insect attack is extremely variable. Some tropical woods are very durable to both fungal and termite attack (teak, iroko); some are only durable to fungal attack (mahogany); but most tropical woods are not very durable. From the temperate zone only a few woods (such as the heartwoods of oak and pine) are considered even moderately durable. Pine sapwood is extremely sensitive to mould and discoloration by stain and should be avoided in furniture for warm and humid climates. Spruce is much better in this respect. Coatings on wood can promote or prevent superficial fungal growth depending on their composition and porosity.

Thin sections of wood are called veneer. These are used as surfaces on less expensive materials, such as chipboard. They are usually applied with adhesives that are not durable under warm humid conditions (PVAc, UF, see the section on Adhesives). The moisture movements in veneer are low in their longitudinal direction, but much higher in their other (tangential and radial) directions. This is an advantage when veneers are used as edgings on boards with high thickness swelling.

Solid wood may be bonded together in many forms. The most common are:

- Finger joints, in which short boards are joined together to produce longer boards. This is common in simple furniture.
- Laminated wood (glulam), in which wooden boards are bonded together into large size beams for construction.
- Bent laminated wood, in which thin strips of wood (veneers) are bonded together in bent shapes. This is a common material in easy chairs and recliner chairs made from beech.

As long as the adhesive is of high enough quality these bonded wood products will function well under humid conditions. The differential swelling of different boards or laminates may, however, show as small distinct steps at each glue joint.

For warm and humid climates, avoid the use of putty or plugged knots. The putty and the adhesive used to plug knots (often hot melts) are not durable under warm humid conditions.

It is also possible to steam bend whole wood to produce bent wood furniture (mostly straight backed chairs). Bent wood is stable at low humidity, but at higher humidity there is spring-back which will put great strain on a piece of furniture.

Recommendation

Timbers with low moisture movements and natural resistance to fungi and insects are usually preferred, but most timbers may be used. Pine and other species that are very prone to discoloration should be avoided. Glue wood with durable adhesives. Do not use steam bent wood.

Board materials

Board materials are the base of most furniture manufacturing in Europe today. They are composed of reconstituted wood particles. Roughly, boards of all types may be divided into three classes or grades (the RH-levels given are rules of thumb for long term exposure):

- interior (RH ≤ 60%)
- moisture protected (also called MP or V313, RH ≤ 80%)
- exterior (also called WBP).

The main difference between these classes of boards is in prolonged, or more significantly, cyclic exposure to water and heat. The interior boards will swell up and disintegrate fairly quickly, whereas uncoated exterior board will swell up, but retain most of its strength, and the moisture protected boards will be somewhere between the two extremes. The differences are mainly caused by the different types of adhesives used. Preservatives and hydrophobic agents are sometimes used in boards.

Board materials are graded with standardized tests. These tests are usually not aimed at testing the products under long term exposure to high humidities and temperatures. In the V313 test the board is exposed to three cycles of boiling – freezing – heating, after which it should retain its dimensions and mechanical properties. The final heating also dries the sample, which is then tested under dry conditions. For the use under tropical conditions, it would be better to test stability, strength and creep under prolonged exposure to warm humid conditions.

Board materials are usually not used in furniture without some sort of coating. The most common is a thin layer of melamine, but paints, lacquers, laminates and veneers are also used. It is essential that both faces of a board are given coatings with the same properties, e.g. the same coating. If not, the board will warp as one of its faces becomes more rigid than the other; moisture may also be more easily absorbed on the uncoated face. For laminated boards one usually applies a counter laminate on the back side.

The most common board material in furniture today is *chipboard (wood particle board)*, made from wood chips and an adhesive. Exterior grade chipboards are uncommon, but moisture protected grades are used in buildings, e.g. as flooring.

A board type used in buildings and as bottoms in drawers and backs in wardrobes is the *fibre board*. It is made by pressing together wood fibres at high temperature and pressure without adhesive. Such boards are usually not well suited for furniture in humid climates as they show high creep.

A modern variety of the chipboard is the *medium density fibreboard (MDF)* made from wood fibre and adhesive. This board type is very popular today in the furniture industry as it is easy to machine and has a compact homogeneous structure. It can be coated without any pre-treatment and the edges can be coated with lacquer instead of edge bands. Most MDF is manufactured in interior and moisture protected grades, but there are also exterior grades on the market (made with polyurethane adhesive) that should be advantageous in humid tropical climates.

The most weather resistant board available today is *plywood*. This is made by bonding together a number of wood veneer plies at right angles to each other. Plywood is the only board that is commonly manufactured in exterior grades, with phenol and phenol-resorcinol adhesives. Phenol impregnated plywood, which is extremely good with respect to moisture, is used in concrete formwork and playground equipment.

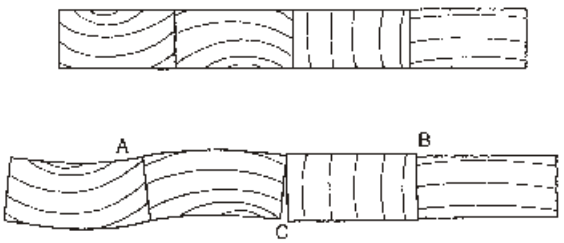
There are also a number of boards made from solid wood: blockboard, edge glued panel, laminboard with thin battens and battenboard with wider battens. These are made by joining together battens of wood to give a board which may be coated with a single wood veneer on each face. The performance of blockboards and edge glued panels under humid conditions depends on

- the width of the battens (thin battens give less deformation)
- the quality of the adhesive (PVAc is not good, see Adhesives)
- the quality of the battens (knots and other fibre deviations give uneven swelling)
- the direction of the grain angle (preferably the same grain angle on both sides of a joint)
- the coating (thick veneers at right angles to the battens give a much more stable product).

If not cross veneered, these boards have high swelling in one of the directions in the plane of the board.

There are also solid laminate boards made from several layers of high pressure laminates. These are very stable under humid conditions.

The swelling of the board materials, except those made from solid wood, is less in the plane of the board than in the thickness of the board. It is also rather similar for all types of boards, as it is mainly determined by the swelling of the wood particles. Typical mean values of length and thickness swelling when the RH increases from 35 to 85% are 0.2 and 3%. As single boards may have twice these values, it is often of greater interest to have specified maximum values than the mean values of swelling. Values of swelling may be obtained from the board manufacturers. Note that interior and exterior boards show similar final swelling, but the exterior boards have a slower and more reversible swelling.



An edge-glued panel is assembled at dry conditions and then brought to a humid location. A number off swelling effects may be seen:

As wood has a higher swelling in the tangential direction than in the radial direction, battens with "mixed" directions will cup. With this type of batten the best board is obtained by alternating the directions of the battens as at A in the drawing.

The higher tangential swelling will also show up as distinct steps where battens with tangential and radial directions are joined (B).

Cracks will develop between battens where neighbouring battens have very different swelling (C). This is often seen near knots and fibre deviations. PVAc adhesive, the most common wood adhesive in carpentry, is not good in this respect, as it cannot tolerate long term stress. Other adhesives (e.g. EPI and PF) are much stronger (do not creep) under humid conditions.

The best edge-glued panel for humid conditions is made with a durable adhesive and thin defect-free battens with similar growth ring orientation in neighbouring battens.

Creep in board materials is very variable. Some chipboards have extremely large creep (especially under warm and humid conditions). Structural chipboard (used in buildings) is better in this respect. Plywood and blockboard have low creep. In climates with varying RH coated boards have less creep than uncoated boards. Creep values are often difficult to obtain from the manufacturers.

All types of board materials are manufactured with adhesives that may contain substances that are hazardous to health. Formaldehyde emissions from chipboard and MDF are regulated in Europe, but it is expected that one will get higher rates of emission at high RH and temperature (Berry et al. 1995). This should be checked with the manufacturer.

Recommendation

Use moisture protected or exterior grade boards that are glued with durable adhesives. MDF, plywood and blockboard should be preferred over chipboard as the former can be used without edgings. Blockboard should be made with thin high quality battens.

Laminates, foils and edgings

Laminates and foils are applied as coatings on board materials to give them a wear resistant and easy cleaned surface. These materials are supplied both as sheets to cover large surfaces and as bands to be used on the edges of boards. There are a number of different types:

- Melamine foils are thin sheets of melamine, usually white, that are very common as coatings on kitchen and bathroom cabinets. They are bonded to the board by the melamine itself under high temperature and pressure.
- PVC (vinyl) foils are often printed with wood grain or other patterns. The bond to the board is by different types of adhesives.
- High pressure laminates are manufactured from layers of paper which are impregnated with melamine or phenolic adhesives. This makes them very durable, both to wear and water. High-pressure laminates may be applied to boards by different types of adhesives. The top paper in the laminate is usually decorated.
- Edge bands of the above three materials or wood veneers are used to cover the edges of boards. Edge bands are usually bonded with hot melts, but there are also other adhesives (e.g. polyurethane) available that are much more durable.

Melamine foils are strongly bound to the board and the bond will not be damaged by high humidities. Uneven swelling of the particles in the board surface may, however, give "telegraphing." Laminates may be glued with various kinds of adhesives. For warm and humid conditions, use a durable adhesive (e.g. phenolic) to increase the life span.

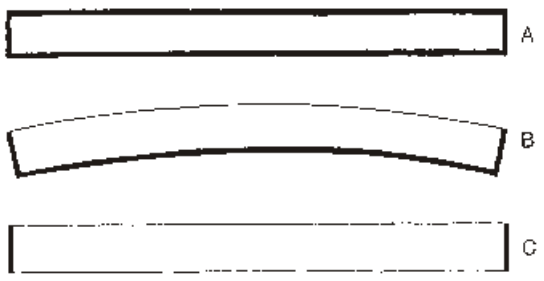
It is important that both surfaces of a board are coated with similar materials. If only one surface is coated with a laminate, the board may warp as the stresses in the board will be uneven, e.g. when the board absorbs moisture and swells. A counter laminate should therefore be placed on the back of a laminated board. For humid climates it is advisable always to use a laminate of the same type and cut in the same direction as the face laminate. Melamine is usually used on both sides of a board.

When the top surface of a board is veneered, one usually applies a vapour tight paper on the bottom face of a board. This paper will stop the bottom face of the board from swelling more quickly than the top face. However, such a paper cannot balance a laminate under humid conditions, as the laminate is much more rigid than the paper.

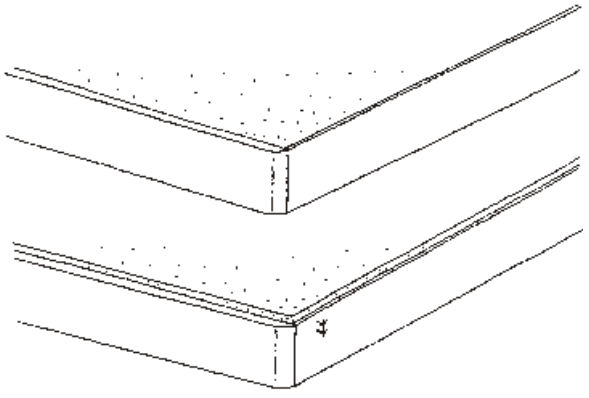
The surfaces of all board materials will be rougher when the boards swell. Sometimes the roughness can be seen through the surface coating ("telegraphing"). Laminates and foils should not be applied on materials that will not retain a smooth surface after swelling; softwood plywood and blockboard with battens wider than 10 mm are not good for laminates. At the time of gluing, laminate and board should be in equilibrium with the same RH, preferably near to the mean RH the furniture will be exposed to in service.

Failure of laminates is usually at the edges. This is both because the edges are exposed to knocks, and because moisture enters and swells the board in the joints between the face laminate and the edging. The latter factor may be partly avoided by the use of post-forming, in which the board is rounded so that the laminate can be curved around the edge of the board. However, the post-formed part, even of melamine foils, is usually bonded with non-durable adhesives, often PVAc, see Adhesives.

The high thickness swelling of the board materials is a major problem. A 22 mm board may swell up to 1.5 mm moving from dry to humid conditions. No synthetic edge band can deform to such an extent. Therefore the adhesive joint will be very stressed. After a few swelling–shrinkage cycles in a composite climate an edging fastened with a hot melt will fail. There is probably no sim-



Three MDF boards absorb moisture in a humid climate. The boards differ in only one respect: they are coated with a laminate on both faces (A), one face (B), or not coated at all (C). When produced, all boards are flat. After absorbing moisture, only board B (with laminate on only one face) shows severe cupping. This is caused by the strong laminate preventing swelling (and moisture adsorption) on the coated face. On the other face, however, there will be a substantial swelling. The other two boards are symmetrical and will not cup.



The figure shows a board covered with a melamine foil. On the edge there is a PVC edging. If the humidity is raised, the board will have a high thickness swelling. As the PVC edging has a comparatively low swelling, the glue joint will be damaged and the interior of the board will not be wholly protected by the edging. This will facilitate the transport of new moisture into the board, thus accelerating the adsorption and swelling processes.

ple solution to this problem when the furniture is exposed to extremely humid or cyclic climates, but these possibilities should be explored.

- Fasten the edge band with better adhesives; there are suitable polyurethane (PU) adhesives on the market, some of which can be used in edge banding machines.
- Leave the edges uncoated. This is certainly possible for wood and plywood furniture, but could maybe also be practised for exterior MDF.
- Coat the whole board with a lacquer which is elastic enough to not be damaged by large moisture movements.
- Fasten the edging with nails or screws.
- Use wooden edgings which will swell and shrink somewhat like the thickness of a high quality board.
- Coat the whole board with extremely vapour-tight coatings to minimize the moisture movements in composite climates.
- Join the edging to the board at high humidity to avoid the high initial swelling.
- Use edgings that only need to be fastened along the centre line (e.g. with a tongue on the edging and a groove cut into the board edge.

Recommendation
Use durable adhesives and laminate both faces. Avoid edge bands if possible, otherwise glue with durable adhesive (do not use ordinary hot melts).

Foams and textiles

Recommendation
The use of foams (e.g. polyurethane) and textiles for furniture to be used in humid tropical climates should be avoided. These materials collect dirt and attract fungi and vermin.

Metal parts
Steel furniture is common in many countries with warm humid climates. Metal parts, such as hinges, screws and nails, are also used in all other types of furniture. It is essential that the metals used do not corrode as this can cause both discoloration and malfunction. It may also be difficult to dismount the furniture if the fittings have corroded.

High humidities are needed for the corrosion processes to start, and corrosion is greatly accelerated by the presence of air borne pollutants and sea salt. Pollutants may come both from industries and from the burning of coal and oil for heating and cooking. Therefore, metal parts have to be of very high quality for humid seaside regions and humid industrial areas. Some wood preservatives also contain salts that accelerate corrosion under moist conditions.

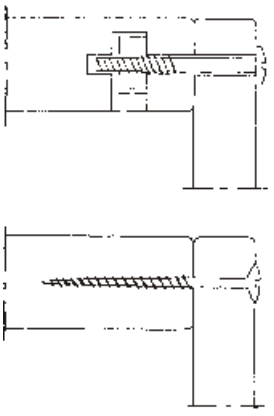
Metal fittings are produced in a large number of different metals and with different coatings. The most durable are made of acid-proof stainless steel which will not corrode even in the presence of salt. Ordinary stainless steel and brass are also very resistant. Aluminium and copper are also good in this respect, even if they are not used much in furniture. Coatings of chromium, nickel and zinc on steel also give some protection, depending on the thickness of the applied layers. Most lacquers and plastic coatings are only aesthetic coatings which gives very little protection. Ordinary steel will corrode very quickly in a humid climate. Many exposed metals such as brass will tarnish in warm and humid climates.

Note that there are a large number of types of each metal. Brass, a mixture of mainly copper and zinc, is, for example, produced in many varieties with different percentages of copper and zinc, and traces of other metals. “Naval brass” is an example of a very corrosion resistant brass. In general, metals used in shipbuilding and process industries are durable to atmospheric corrosion.

Stainless steel and brass are good as these materials do not corrode. The properties of the coatings (chrome, nickel, zinc, and lacquers) are determined by the thickness and integrity of the applied coatings. Coated ordinary steel should never be used when there is a risk that the coatings will be damaged by handling or wear.

Modern furniture hinges and drawer runners are complicated components, each consisting of up to a dozen subparts of different materials. Normally all such parts are made of high quality materials (e.g. with coatings of nickel or epoxy), but it is recommended that their durability under warm humid conditions be discussed with the manufacturer. Springs in hinges are sensitive as they are not very resistant to corrosion.

Metal parts are used to connect or strengthen wooden parts. In all such cases the moisture movements of the wood material should be considered. A metal angle band is sometimes used to strengthen a thin laminboard. As the wood may show large moisture movements, it must be screwed to the wood through oval holes in the metal band, to permit these movements. The same applies to all long metal parts, such as piano hinges. Many modern do-it-yourself pieces of furniture use connecting screws with cross dowels that can accommodate quite large moisture movements in the joints.



Do-it-yourself furniture is often assembled with connecting screws with cross dowels (top). This can be a flexible connection that can take relatively large moisture movements without loss of strength. In a composite climate, with large annual moisture movement, it is probable that the wood becomes compressed. The function of the joint is easily restored by tightening the screw. A traditional wood screw (bottom) makes a joint with less flexibility.

Recommendation
Never use ordinary steel, or ordinary steel coated with lacquers or ordinary plastic coatings. For non-polluted, inland sites thick coatings of zinc, nickel or chromium may be used for parts not subjected to wear. For polluted or seaside locations only stainless steel and brass can be recommended. Discuss the use of durable coatings, e.g. epoxy, and metal springs with the manufacturer.

Plastics and elastomers
In many cases modern furniture contains a number of plastic parts, such as handles and rollers. In some cases whole pieces of furniture are made in plastics. Most plastics are durable under moist conditions, but lose strength and rigidity at high temperatures. The indoor temperature in tropical climates is never high enough to cause immediate failure in any plastics used in furniture, but it is advisable not to use load bearing plastic components in warm climates unless it is known that the plastic materials are guaranteed to function under such conditions.

Most plastics are sensitive to UV-radiation from the sun and will deteriorate quickly outdoors, especially in countries near the equator. Indoors the level of UV-radiation is much lower, but the service life of plastic parts will still be lower in countries with higher levels of solar radiation. Indoor furniture with plastic parts should not be left outdoors in the sun.

The thermal expansion of plastics is high compared to other materials. A 2 mm expansion per meter is possible for a temperature rise from 20 to 30°C. As plastic parts usually are small, this expansion will seldom cause any problem in furniture.

Recommendation
Do not use load bearing plastic parts and do not expose indoor furniture with plastic parts to the sun.

Adhesives
Adhesives (glues) are used in nearly all types of furniture: chipboard and MDF boards are made from wood and adhesives; laminates and edgings are bonded with adhesives; blockboard, edge glued panels and plywood are made by bonding together wood battens or veneers; many furniture parts are also assembled with adhesives.

The following types of adhesives are extremely durable under humid conditions:

- Phenol Formaldehyde (PF)
- Resorcinol Formaldehyde (RF)
- Phenol Resorcinol
- Emulsion Polymer Isocyanate (EPI)
- Polyurethane (PU, both 1 and 2 components)
- Epoxy (some types).

Less durable, but probably sufficiently durable in most tropical applications, are:

- Melamine Formaldehyde (MF)
- Melamine Carbamide (with a minimum of 50% melamine)
- Epoxy (all types)
- Acrylate adhesives.

Polyvinylacetate (PVAc, PVA) with acid hardener is also quite durable, but should not be used under load because of high creep. The most commonly used adhesives in the furniture industry: PVAc without hardener ("white glue"), Urea Formaldehyde (UF), ordinary hot melts, and rubber (contact) adhesives are for "interior" use only. They are not durable under warm humid conditions. These adhesives may still function for some time under humid conditions if the joint is not exposed to stresses. All PVAc adhesives deform under stress (creep) and failure can occur under relatively low loads in warm and humid conditions. Ordinary hot melts should never be used in furniture which may be exposed to warm conditions during transport or in use, as they will begin to soften at moderate temperatures (40°C). There are, however PU hot melts that are more durable.

Some of the glues listed are primarily used for wood and wood products (UF, MF, RF, PF, PVAc) while others may be used for different kinds of materials, such as wood, metals, plastics and glass. All the more durable glues (except the 1 component PU) are two component products that are more difficult to handle than ordinary PVAc glue. Some of the glues above are not colourless (e.g. resorcinol).

Unfortunately, the use of the more durable glues also involves more health hazards than the use of the more common furniture glues. Unhardened PU, EPI and epoxies contain substances that can cause allergic reactions. UF, MF, RF and PF all harden by reactions involving formaldehyde, some of which may be left in the product and be emitted to the surroundings. Formaldehyde is an irritating gas which also can cause allergic reactions (Berry et al. 1995). These products cannot replace PVAc and hot melts without changes in production to handle these adhesives correctly.

One should not overrate the possibilities of making durable wooden furniture by using durable adhesives. Adhesive joints are only a tiny fraction of a millimetre thick and cannot take up large deformations. If a very strong glue holds swelling wood pieces together when they want to warp, the wood may break instead. The strongest adhesive is not the best glue.

The best glue for high humidity and large moisture movements should be moisture resistant and produce bonds that are somewhat flexible. The latter property is important as it will decrease the stresses in the wood near the bond when the joined pieces have different swelling. EPI and PU adhesives have these properties and could be used where the adhesive joint will be stressed by differential swelling or dynamic forces, such as in a chair.

Recommendation
Do not use ordinary PVAc, hot melts, urea-formaldehyde or rubber adhesives. Instead use more durable adhesives such as PU, EPI or any of the phenol/resorcinol/melamine-formaldehyde glues. Follow the instructions for use of new adhesive products carefully.

Coatings
Coatings are used to give a good appearance to furniture, to protect it from wear and moisture, and to make it easy

to clean. It is of course also essential that the coating itself is durable in the humid climate.

It is impossible to protect furniture in *constantly* humid climates from the humidity. The only use of a coating is to dampen *variations* in moisture conditions (see Fig. 7c). This will decrease the moisture movements and prevent large differences in moisture distribution within a furniture component. Note that it is important to apply coatings on all surfaces for effective prevention of moisture sorption. End-grain, e.g. ends of chair legs, should also be coated as the moisture transport is highest in the longitudinal wood direction.

To lessen the risk of mould growth on coated surfaces, the coatings should be non-porous and not contain substances that can be digested by fungi. Similar looking coating products can have very different resistance against mould.

Coatings are a very complex group of materials usually containing a large number of components. Moreover, a coating of one type can be formulated in various ways to suit different needs, e.g., very different types of polyurethane coatings are used on wood and as car lacquer. It is difficult to give any general advice on which type of products to use.

The most durable and most vapour-tight coating for wood materials is polyurethane lacquer which is used for high quality furniture. Some outdoor paint systems, e.g. alkyd based, are also durable and quite vapour-tight, but do usually not have a very high finish.

The most common coatings in the furniture industry, e.g. acid and UV hardening systems, are usually not guaranteed to be durable in warm humid climates. Advice should be sought from the manufacturer as there are large differences between products.

Surface treatments in tropical climates are traditionally with oils or waxes. These treatments can stand the high humidities well, but have very low resistance to moisture flow, e.g. furniture coated with such products will essentially behave as uncoated furniture.

The use of coatings involves health hazards from solvents and other substances. Some coatings, e.g. outdoor paints, may also contain fungicides and should not uncritically be used indoors.

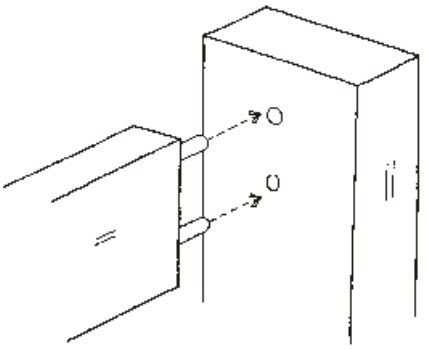
Recommendation

No general advice can given on which products to use. Contact the manufacturers of the coatings for advice. Look for coatings that are flexible, vapour-tight, and mould-resistant (non-porous).

Design

This section is short as the design and construction of furniture is discussed together with material properties and in the case studies. Only some general advice is given.

Moisture movement is the main design problem for wooden furniture for warm and humid climates. Therefore minimize the distances where materials with different swelling characteristics meet, e.g., instead of one very wide tenon, use two shorter ones.



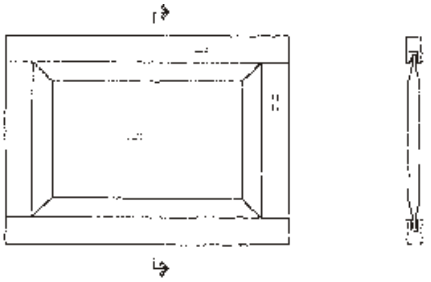
Two holes are drilled into a leg to hold two dowel pins from a stretcher. Before the pieces are joined their MC increases from 8 to 18%. As the wood does not swell appreciably in the longitudinal direction, the distance between the holes will not change. The spacing between the dowel pins, however, will increase. As a result the dowel pins will not line up with the holes. (Drawing exaggerated to illustrate the principle.)

Short joints and joints between similar materials (in similar directions) are preferable.

It is not a good idea to try to fix materials so that they cannot swell or shrink, as this may give rise to very high stresses. It is always better to allow materials to move freely, and consider their natural behaviour.

The absolute moisture movements are proportional to the length of a piece of material. Therefore, do not use long wooden furniture components if they cannot swell freely, e.g. do not fix a chipboard top to a steel frame without allowing for moisture movements.

Even in temperate climates, furniture joints are damaged by humidity variations. In humid composite cli-



The frame panel door shown is made of solid wood. It is a traditional type which is good under conditions of varying humidity. The frame parts are ell in the longitudinal direction and have low moisture movements. The central panel, however, has a very large swelling in one direction and must therefore have the possibility of expanding into the frame (i.e. it must not be glued). If this type of door is going to be used under conditions of large variation in moisture content, the expansion grooves in the frame must be rather deep. A 400 mm pine panel manufactured at 8% MC and used at 18% MC will swell approx. 10 mm. Coatings used must not be allowed to act as adhesives in the expansion groove.

mates joints may loosen after only a year or two as a result of compression set. It may be an advantage to use joints that can be tightened when loose, e.g. screw joints. Glue joints can be repaired when loose.

In composite climates it is possible to decrease moisture movements by sealing the whole furniture with vapour-tight coatings or laminates. To do this effectively, however, requires that the whole furniture is sealed. Some calculations and knowledge of the properties of the materials used are also needed.

Tendering

Recommendation: The following advice is given to those tendering furniture on a large scale in Europe for use in a humid tropical climate.

1 Find out the approximate type of climate that the furniture will be exposed to (constant humid, or composite).

2 Check if it is possible to use simple, local, unconventional or low-cost local furniture. This is often better.

3 When writing tendering specifications, state under which conditions the furniture is to be used, and what service life you expect from them. The use of durable adhesives, moisture proof or exterior boards, and corrosion resistant metal components could be called for, but it is probably not relevant to describe in detail the materials and designs that should be employed.

An example of a tendering specification is:

Type of furniture:	*chair with arms*
Intended Use:	Staff houses
Number of pieces	100
Expected service life	10 years
Guarantee time	2 years
Climatic conditions of use	constant warm and humid (maximum 30°C and 85% RH) seaside location (Singapore).

Materials and design should be described in detail with emphasis on the condition that the proposed furniture achieve the intended service life under the stated conditions. All materials used must be durable under warm and humid conditions. Note particularly that adhesives must be durable, board materials should be of “exterior” quality, and that all metal parts must be corrosion resistant.

To this specification you should add any other requirements you have.

4 Make sure that the manufacturers have understood that you are serious in your demands, and that they have the knowledge to give you what you want. Remember that most of the furniture in Europe today is produced in long series and sold off the shelf for European indoor use and may not function in a warm humid climate.

It is probable that many furniture producers are unaware of the problems with furniture exposed to humid tropical climates, as this is a very small market for them. Some may also believe that they will never hear any complaints if their furniture is sent to foreign destinations. Note that product guarantees of quality, such as *Möbelfakta* in Sweden and the *NF* label in France, do not cover durability under tropical conditions.

5 The manufacturer should give a detailed description of the furniture he wants to sell, including:
- materials used, including adhesives and coatings, and evidence that these are durable;
- a general description of why the piece of furniture will be durable under the conditions of the specifications;

If you do not have the experience to decide whether the proposed furniture will have the intended service life, you should contact an expert for help.

6 It is always best to have wooden furniture produced at equilibrium with the mean RH of the intended place of use. It is usually not possible for European manufacturers to use any other moisture conditions than those appropriate for European use. An alternative is manufacturing in a region with more humid climate.

7 Make sure the furniture is handled well during transport. Shipping furniture from Europe to a tropical country can be more damaging than the warm humid climate itself. This is because of the extreme temperatures inside transport containers left in the sun. In some cases it may be better to send the furniture unassembled by air.

8 Instruct the users of the furniture in its care. Furniture should not be cleaned with a damp cloth more than necessary. Never use too much water.

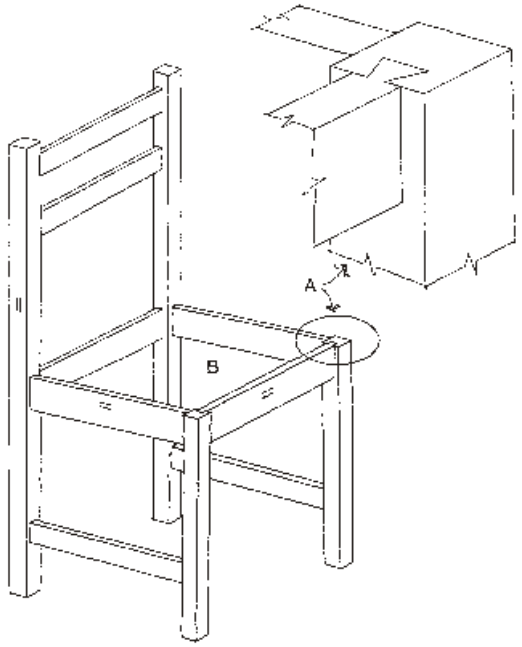
9 When large amounts of furniture are sent to a warm and humid climate, it is advisable to assess the performance of the furniture at suitable intervals during its estimated service life. If this is not done, the furniture may not be functioning as intended; you cannot improve your tendering specifications; and the manufacturer cannot improve his products. The first control of the furniture should be made before the guarantee expires.

4 Case studies

These case studies are desk studies that highlight critical parts of furniture under warm and humid conditions. Each case study contains a drawing and a description of the furniture, and a drawing marking the interesting points. In some drawings the fibre direction is marked with two parallel lines.

Traditional chair

Solid wooden chair of a traditional type.



A Chairs are probably the type of furniture exposed to the highest dynamic loads, e.g. when they are tilted. The traditional wooden chair is a strong construction in which the swelling of wood does not cause much problem. The main concern is that quite long joints are needed to join the frame parts to the legs. The dovetail joints in the two front legs, if not wholly glued, permit the wood to swell and shrink. The joints in the rear legs are simple mortise and tenon joints which may be problematic, since they usually are wholly glued with PVAc, although the traditional type of wood pegs may be used instead to fix the joint. If a joint becomes loose it is usually quite easy the repair it with a new adhesive (1 component polyurethane is an easy to use durable adhesive).

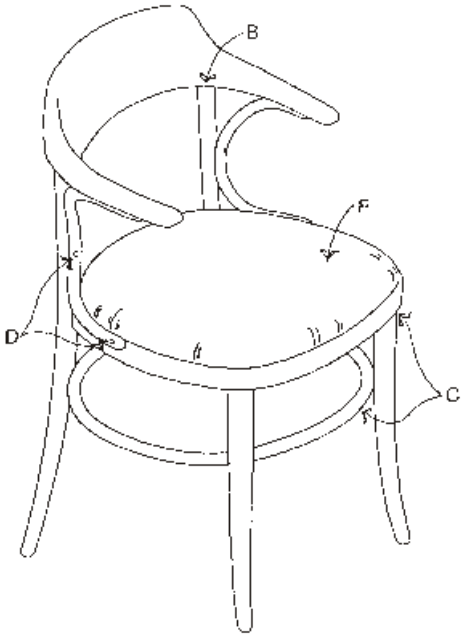
B Attaching a solid wooden seat to the chair frame is problematic. The seat will have large moisture movements in one direction and may cup or warp. A seat of a moisture resistant board material, such as plywood, is better as this material has about the same swelling as wood in its longitudinal direction (the frame of the chair). Normally seats are covered with an unattached cushion, which may be problematic in a very humid climate. A jute webbing seat is also good.

Conclusion

This type of chair is quite satisfactory in tropical climates. The seat should not be of solid wood or covered with any textile materials. Joints should be glued with a durable adhesive.

Bentwood armchair

This chair is made from steam bent beech. All parts are screwed together, except the joints in the backrest. The whole chair is lacquered.



A Steam bent beech is not stable under very humid conditions and spring-back will place large stresses on the structure. Minor dimensional changes, however, will not be a problem as there are no long joints in this framework structure, which is both strong and flexible.

B The pin joints in the backrest may loosen after a while as there will be unequal swelling in the two parts of these joints.

C The frame of the seat and the O-shaped piece below it are made as steam bent pieces with a scarf joint and a finger joint, respectively. The joints are glued with PVAc; a more durable adhesive would have been better as there will be stresses in the joints if there is spring-back in the bent parts.

D The screws used should be corrosion resistant and not drawn too tightly if the chair is assembled in a dry climate.

E All parts of the furniture may be coated with lacquer to minimize moisture movements (also leg ends and other hidden parts).

F In a humid climate, the seat should be veneered (plywood) as fabrics will get mould stains.

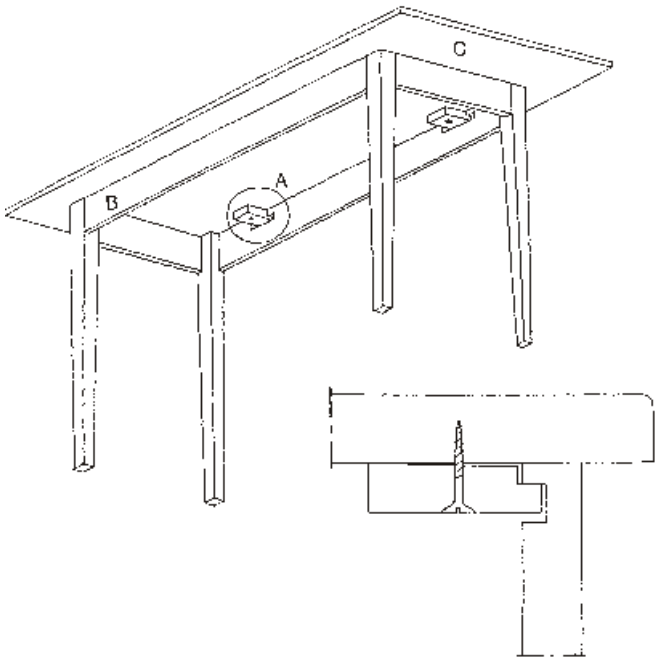
Conclusion

For constantly humid conditions bentwood furniture is not recommended as the bent parts will spring back. This

applies to all wood species used for bending. If coated all over with a vapour-tight coating, it could be used in a composite climate. The construction is extremely strong as long as the bent parts retain their shape.

Dining table

A simple traditional dining table (seen from below). The top is a solid wood board, edge glued, and the undercarriage is made from wood. The top is fastened to the undercarriage with four blocks of wood (A).



A This way of fastening the top permits large moisture movements in either direction of the top. This is an example of a traditional design that works well under conditions of large moisture movement.

B This joint may cause problems as the cross member has larger moisture movements than the leg. The problem can be decreased by not making the cross member as high, but then the table will be less stable. The joint can also be made to allow some movement, e.g. a dovetail joint which is only glued at one point.

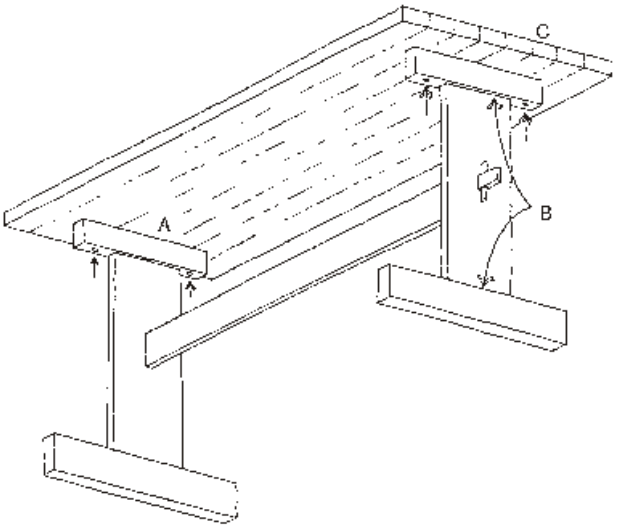
C A wooden table top has large moisture movements in one direction in the plane of the board. It may also become wavy and crack at high humidities as the battens can have different swelling. Board materials such as plywood, chip board, MDF are superior in this respect, as these materials have a very much lower swelling in the plane of the board. The quality of edge glued boards is discussed in the section on Laminates, Foils and Edgings.

Conclusion

This is a good design, but the top should not be made of solid wood unless the battens are thin and with straight grain. Laminated exterior MDF or exterior plywood is better.

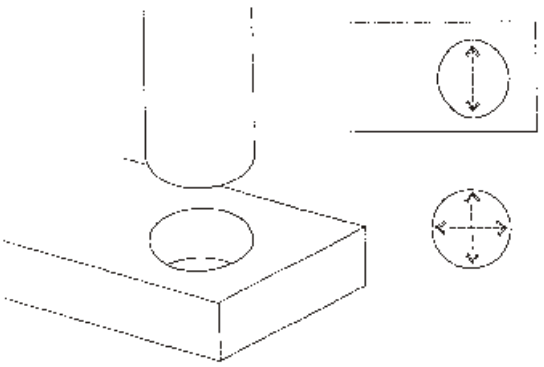
Rustic dining table

This traditional table is made from solid pine. The top is fastened to the undercarriage with two screws on each side (marked with small arrows).



A The table top will swell up to 10 mm on the 500 mm distance between the two screws as RH increases from 35 to 85%. The cross-member is in the fibre direction and will not swell appreciably. If the top is simply screwed to the undercarriage, these screws will probably be damaged. The top may be fastened with more flexible fittings (like screws in oval holes). Pine is not a good material for warm and humid places, as the sapwood is easily attacked by fungi (blue stain, mould).

B A similar situation exists for the two joints at B that are 250 mm long. The adhesive joint will be damaged.



A hole is drilled into the side of a wood board with moisture content MC = 8%. After being exposed to a humid climate for some time, its MC = 18%. As the wood swells mostly across the grain it will now be oval and larger (solid line). (Drawing exaggerated to illustrate the principle.)

A wooden rod, which fit the hole snugly when both pieces were at MC = 8%, will swell in both directions across the grain in the humid climate (dashed line). Consequently, it will no longer fit into the hole. If the pieces were assembled at low MC, the wood may crack as the rod expands more than the hole.

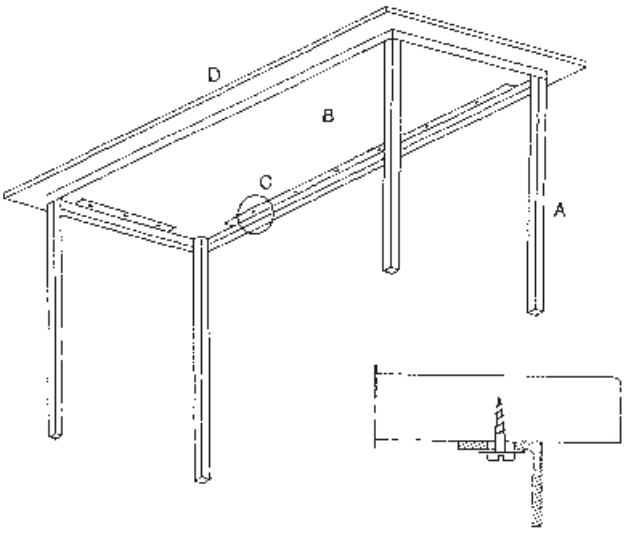
C The edge glued top is usually made from square battens of rather low quality, containing knots, etc. Under increased moisture content the PVAc adhesive joints will be damaged as the swelling in the battens is not uniform. A better adhesive and battens with more uniform moisture movements will make a better top. The quality of edge glued boards is discussed in Laminates, Foils and Edgings.

Conclusion

This is not a good design for warm humid climates, both because of the large differential moisture movements of the thick wood components and the wood (pine) whose sapwood is very sensitive to stain and mould.

Work table

The undercarriage of this work table is made from lacquered steel. The desk top is made from 18 mm high pressure laminate faced chipboard with PVC edge bands. The bottom face is paper coated. The top rests on a flange on the undercarriage and is fastened to it with screws.



A The coating of the undercarriage should prevent corrosion of the steel. It should also be strong enough to resist scratching and wear.

B Under constant warm humid conditions the impregnated paper of the bottom face is not enough to keep the board symmetrical. It is better to use a high pressure laminate on the bottom face as well.

C The swelling of the chipboard in the plane of the board is low, but it still amounts to 4 – 5 mm over the 2 m length of the table if the RH increases from 35 to 85%. This will impose stresses on the structure as the steel does not swell; the thermal expansion of steel in a warm climate is negligible compared to the wood swelling. A solution is to fasten the board with screws in oval holes which permits the board to move in one direction. It is also be possible to use large holes permitting movements in two dimensions. The screw would then have to have a large head or be used with a washer.

D The edging is bonded to the chipboard with a hot melt adhesive. This is not acceptable under warm conditions as such adhesives begin to lose their strength at 40°C. A better adhesive will hold the edging tighter.

Conclusion

A construction that can be improved in four ways for warm humid climates:

1 Larger holes in the undercarriage to permit moisture movements of the top.

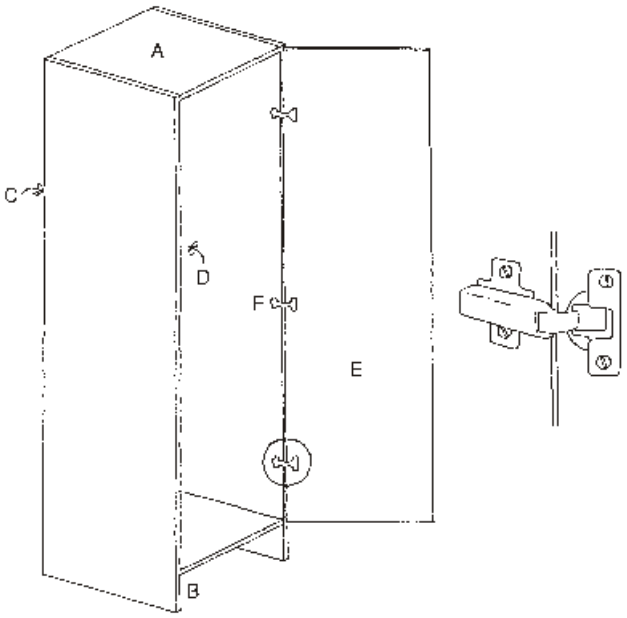
2 Make sure the frame coating is durable under warm humid conditions.

3 Apply a high quality counter laminate on the bottom face.

4 Bond the edge band with polyurethane or any other durable adhesive.

Wardrobe

A wardrobe made from 15 mm melamine faced chipboard, with a back of 4 mm fibreboard. The rear edges of the boards and the back of the fibreboard are not coated.



A The chipboard is of interior quality and is not guaranteed to be stable above 60% RH. A higher quality chip board (V313 or WP), exterior MDF or plywood would be a better choice for a humid climate. If an interior chipboard is exposed to high humidity, or even worse high cyclic humidity, the board will have high irreversible thickness swelling and begin to lose its strength and rigidity. In this case, the coating of melamine may help the board to retain its shape.

B The edgings are often the most heat and moisture sensitive part of a piece of furniture. The adhesives used are not moisture resistant, and the board has a high thickness swelling under humid conditions. High cyclic humidity will soon give fatigue in the adhesive joint. A better adhesive, such as polyurethane, will help to keep the edgings in place.

C Normally, all board edges that are not visible are left uncoated. In a climate with frequent cyclic humidity changes it is advantageous to seal all surfaces to minimize moisture movements.

D The back is made of a thin fibreboard which is not very moisture resistant and often fixed with nails of ordinary steel. This is not recommended as the integrity of the wardrobe depends on the back. Use corrosion resistant nails.

E When the door is closed it rests on the outside of the carcass boards. This is good as the door cannot get stuck.

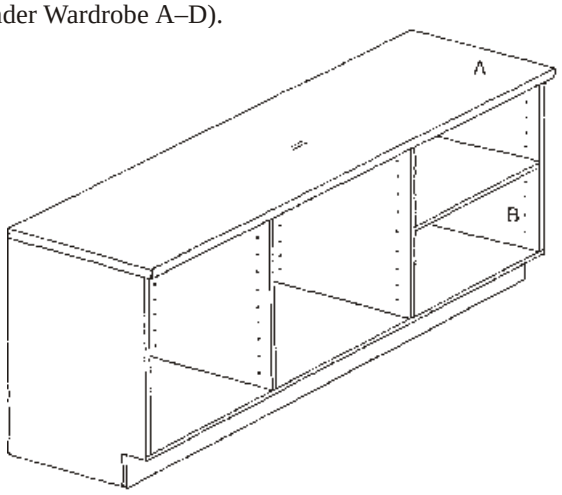
F The hinges should be very well fastened as the chipboard will soften as its moisture content increases, and the door is quite heavy. All parts of the hinges should be made of corrosion resistant materials.

Conclusions

Are closed wardrobes necessary in warm humid climates? A better wardrobe would be open, made of exterior plywood or exterior MDF with a durable lacquer as coating on all surfaces. All parts of hinges should be made of durable material. If doors are necessary, they can be constructed with louvers or screens.

Kitchen cabinets

A set of kitchen cabinets of melamine faced chipboard. The workbench is made of beech laminboard (also see under Wardrobe A–D).



A The workbench will have much greater moisture movements than the chipboard in the direction perpendicular to the length of the bench. If the RH increases from 35 to 85%, a 600 mm beech bench will swell up to 20 mm, while the chipboard swells only 1 mm. The workbench will tear the chipboard apart. It is therefore not a good idea to fasten the workbench to the cabinet both at the front and at the rear. If it is to be fastened at all, one set of fasteners at the rear would be the best option. It is also possible to leave the workbench unfastened, since it is heavy and will stay in place if there is some material with high friction between it and the melamine. A workbench of chipboard or plywood would be better, as it will have much the same swelling as the cabinets.

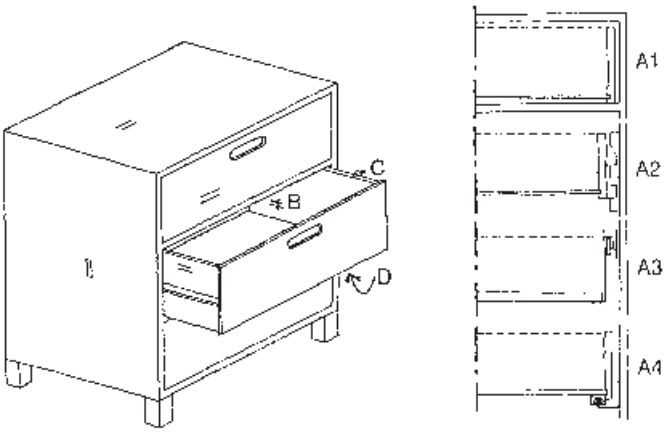
B It is better not to have all the small drilled holes through the melamine foil as the moisture movement in a variable climate will be much more rapid here causing the melamine to crack near the holes. Mould and vermin may also grow in these holes.

Conclusion

A better construction could be made from exterior plywood or exterior MDF. The melamine on the face of the boards is good in a kitchen. If edge bands are used, they should be bonded with polyurethane or some other durable adhesive. Do not drill more holes through the coating than necessary.

Chest of drawers

This chest is made from untreated pine and thin fibre board for the bottom of the drawers. The short double lines show the longitudinal direction of the wood, and the figures on the right show examples of different glide devices for drawers.



A Four types of drawer runners are shown in A1–A4.

A1 The drawer simply rests on the wood.

A2 Wooden strips on the sides of the drawer rest on wood strips on the sides of the chest.

A3 A modern type in which the side of the drawer is made of plastic or steel and rolls on a low friction wheel fastened in the side of the chest.

A4 A modern concealed drawer runner, in which the aluminium drawer runs on ball-bearings.

The traditional drawer types may get stuck inside the chest under humid conditions. Using board (chipboard, MDF or plywood) for the drawer sides eliminates this problem, but then the drawer front should also be made of the same material.

Modern type drawers do not have these types of problems as the sides of the drawers are not made of wood. The materials used, plastics, steel, aluminium, must, however, be durable under warm humid conditions. Modern drawer runners (A3, A4 above) usually have several possibilities of adjustment and are not sensitive to moisture movements.

B The drawers will easily jam at B in a humid climate as the fronts of the drawers swell. Normally the free space between two drawer fronts is less than 2 mm. As each drawer is about 200 mm high, it can swell 3 – 4 mm (35 to 85% RH) and then be effectively stuck. The problem can be overcome by reducing the height of the fronts.

C As the swelling of the top of the chest and the front of the drawers will be the same (same directions and thicknesses), the drawers will not jam at C.

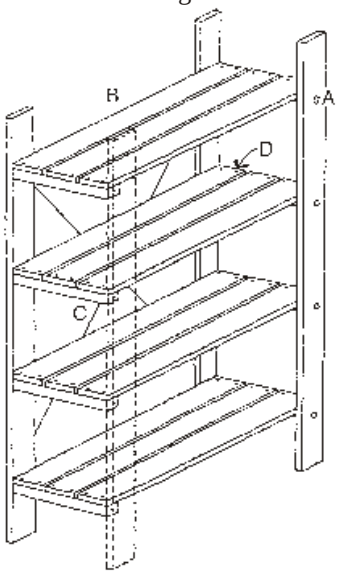
D Thin fibreboard is not an ideal material under humid conditions. If heavy objects are put in the drawers the bottom may creep and eventually fall out of the drawer. If the bottom is fastened with nails or staples, these must be corrosion resistant.

Conclusion

The wood material is not good as the pine sapwood easily becomes stained and fouled by mould. The design is good if it can be shown that the drawers will not get stuck with moisture movements. All parts of drawer runners must be made of corrosion resistant materials.

Wooden shelving

A simple storage furniture made from uncoated spruce wood joined by nails (shelves) and hexagon headed wood screws (legs to shelves). The metal cross support is screwed to the rear legs.



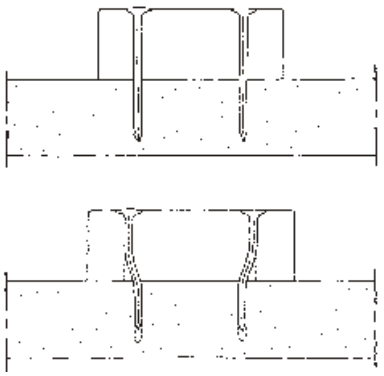
A The shelves are fastened to each leg with only one screw. This is good as the moisture movements will not damage the construction. The screw should be made of corrosion resistant material.

B Each shelf is made of three boards fastened at their ends to cross members. In this way, moisture deformations (e.g. twist) in the individual boards will be reduced.

A shelf has to be designed to take high loads, as it is probably the single furniture component with the highest static long-term load. In this case the shelving is made from 18 mm wood. This is recommended as wood has a relatively low creep. Thinner wood or board materials (MDF and chip boards) can be expected to sag markedly after being loaded for a few years in a humid climate.

C The cross support is necessary as the whole shelving would otherwise fold itself sideways. The cross support and the screws by which it is fixed to the shelving should be made of the same corrosion resistant material. This is most important for the screws as the stability of the shelving depends on them.

D Each shelf board is fastened at each end with two nails, 50 mm apart. Large annual changes in RH may eventually give fatigue in the nails or cracks in the wood. The nails should be made of corrosion resistant material.



Two nails are used to hold a piece of wood to a chipboard. When the humidity is raised, the wood will swell across the grain. As the chipboard swelling is low, the nails will be stressed. If the climate has high annual RH variations the nails may break or loosen after a few years of moisture movements. (Drawing exaggerated to illustrate the principle.)

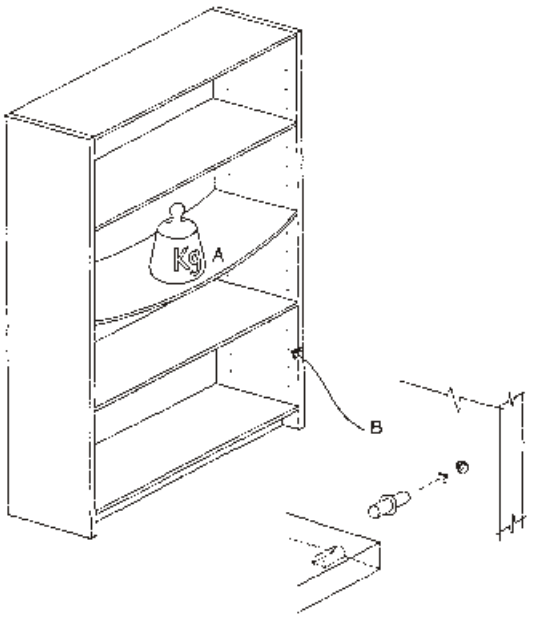
Conclusions

This furniture is a good example of a wood structure in which all parts are arranged so that the high transversal moisture movements will not cause any damage. The metal parts should be corrosion proof. The wood may have to be coated or treated against mould and stain in a constantly humid climate.

Board shelving

This shelf is made from thin veneered chip board. The carcass is assembled with dowel pegs and connecting screws with cross dowels. The shelves are put on small metal supports inserted into the holes drilled through the veneer on the inside of the carcass.

A This is a dangerous design in humid conditions. Normal (interior) quality chipboard will not stand humid conditions. A shelf is probably the most heavily strained piece of furniture, and at high RH the chipboard will have very high creep. One shelf is shown deformed under load.



B The small shelf bearers (see insert B) are strong enough to stand the load, but the holes in the chipboard carcass or the shelves may be deformed at high RH. It is very probable that the shelves will break down if loaded with books in a humid climate.

Conclusions

This is not a good furniture for warm humid climates as the small shelf bearers may not function. A better construction could be made from exterior grade plywood or veneered blockboard made with durable adhesives.

Word List

absorption	uptake of water vapour or liquid water in a material
angle band	a thin steel profile, usually with an L-shaped cross section
batten	a thin board or strip of wood
blockboard	a board made from edge glued wood battens
carcass	the framework of a structure
Compositea climate	climate with large annual variations in RH
compression set	when wood is irreversibly compressed as a result of restrained swelling
creep	long term deformation under load
cup	a form of warp; deviation from flatness across the width of the board
desorption	drying out of water vapour from a material
dovetail joint	a classical carcass joint with interlocking parts (see page 17, left figure)
drawer runner	any object which makes it possible to easily pull out a drawer
early wood	low density wood cells formed in the spring in temperate climates
edge band	any band shaped material used to cover the edges of boards
edge glued panel	a solid wood panel made by gluing together wood battens
edging	similar to edge band
end grain	a wood surface facing in the longitudinal direction
fumigate	treat with gaseous poisons
fungicide	a substance used for destroying fungi
grain angle	the angle to the general direction of fibres in a piece of wood
heartwood	the inner part of a mature tree trunk
hexagon head wood screw	a strong wood screw which is drawn with a spanner into pre-drilled holes
hydrophobic	water repellent
insecticide	a substance used for killing insects
kiln-drying	drying under controlled conditions in a heated chamber
laminate	thin layers of material bonded together into strong sheets
late wood	high density wood cells formed in the summer in temperate climates
longitudinal	a direction in wood (cf. Fig. 8)
MC	moisture content
MDF	medium density fibreboard
melamine	a synthetic resin used to make adhesives, also used as a surface coating on chipboard
Moisture movements	swelling and shrinkage
mortise	a hole or slot made in wood to receive a tenon
oven dry	dried to constant weight at 105°C
piano hinge	a long hinge of the type used to hold the lid of a piano
plugged knots	when knots in wood are removed and replaced by wood plugs
post forming	usually to shape the edges of boards so that the same laminate can be used on the edge and face of the board
preservative	a fungicide or insecticide
putty	a compound used to patch woodwork defects
radial	a direction in wood (see Fig 8)
RH	relative humidity
sapwood	the outer part of a tree trunk
scarf joint	joint between boards where the edges are cut on a diagonal to give a greater contact surface
stretcher	a piece of wood serving as a brace
tangential	a direction in wood (see Fig. 8)
telegraphing	when moisture related unevenness of a board can be seen through a laminate or a foil
temperate climate	a climate that is not subjected to prolonged extremes in hot or cold weather
tenon	the end of a piece of wood shaped for insertion into a mortise
thickness swelling	moisture movements perpendicular to the plane surface of a board
transversal	tangential and radial
tropical climate	warm or hot climates, usually defined as climates with mean annual temperatures above 20°C.
vapour-tight	with a high resistance to water vapour transport
warp	any distortion of the intended shape of a piece of wood

References

Some good sources, not necessarily cited in the text. The subjects of some of the sources are given in parentheses.

Adamson, Bo and Olle Åberg
1993 *Design for Climatization; Houses in warm-humid areas.* Building Issues 5(1). Lund: Lund Centre for Habitat Studies, Lund University.

Berry, R.W.
1993 *Timber in Tropical Building*. Overseas Building Note 199. Watford (UK): Building Research Establishment.

Berry, Roger, John Boxall and Derek Crump
1995 *Health Hazards of Building Materials*. Building Issues 7(1). Lund: Lund Centre for Habitat Studies, Lund University.

BRE
1984 *Timber Selection by Properties*. Watford (UK): Building Research Establishment.

Dinwoodie, J.M.
1981 *Timber, its Nature and Behavior* (wood and boards). New York: Van Nostrand.

Farmer, R.H.
1972 *Handbook of Hardwoods*. Watford (UK): Building Research Establishment.

1977 *Handbook of Softwoods*. Watford (UK): Building Research Establishment.

Forest Products Laboratory
1957 *Shrinking and Swelling of Wood in Use*. Report no. 736, Madison, USA

Hoadley, R.B.
1994 *Understanding Wood*. USA: The Taunton Press. (A practical guide to wood technology discussing moisture movements, joints, strength of wood, etc.)

Koenigsberger, O.H., T.G. Ingersoll, A. Mayhew, and S.V. Szokolay
1974 *Manual of Tropical Housing and Building Part one: Climatic Design*. London: Longman.

Landsberg, H.E., editor
1969–1984 *World Survey of Climatology* (Vol. 5: Northern and western Europe; Vol. 6: Central and Southern Europe; Vol. 7: Soviet Union; Vol. 8: Northern and eastern Asia; Vol. 9: Southern and western Asia; Vol. 10: Africa; Vol. 11: North America; Vol. 12: Central and south America; Vol. 13: Australia and New Zealand). Amsterdam: Elsevier.

Marra, A.A.
1992 *Technology of Wood Bonding*. New York: Van Nostrand Reinhold. (Adhesives and glues).

Mossberg, B.
1990 *Termites and construction*. Building Issues 2(1). Lund: Lund Centre for Habitat Studies, Lund University.

Pearce, E.A. and C.G. Smith
1990 *The World Weather Guide*. London: Hutchinson.

Pudeck, J. and B. Stillefors
1991 *School Furniture; Low cost furniture for developing countries*. Stockholm: SIDA.

1993 *Adobe School Furniture Handbook; A manual on construction of furniture from mud*. Stockholm: SIDA.

River, B.H. and E.A. Okkonen
1991 *Delamination of Edge-glued Wood Panels; Moisture effects*. USA: Forest Products Laboratory Res. Note 0259.

Skaar, C.
1988 *Wood-water Relations*. Berlin: Springer-Verlag. (The science of sorption and swelling).

Spence, R.J. and D.J. Cook
1983 *Building Materials in Developing Countries*. John Wiley & Sons Ltd.

Wadsö, L.
1994 *A Small Simulation Study of Moisture Content Variations in Furniture in Different Tropical Climates*. TVBM-7081. Lund: Department of Building Materials, Lund University.

1995 *An Experimental Study of the Behavior of Some Common Furniture Components in an Extremely Humid Climate*. Lund: Division of Building Materials, Lund University.