Energy saving through the utilization of the thermal behaviour of heavy buildings, based on new materials, building frameworks and heat storage systems.

Final report of a project within Cerbof 2 (www.cerbof.se)

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The results of the project are available on
http://www.byggnadsmaterial.lth.se/forskning/cerbof_projekt/.

The following persons have worked actively within the project.
Ronny Andersson, Cementa AB
Victoria Bonath, Structural and Construction Engineering, LTU
Mats Emborg, Structural and Construction Engineering, LTU
Eva-Lotta Kurkinen, SP Borås
Ulf Ohlsson, Structural and Construction Engineering, LTU
Anders Rönneblad, Cementa AB
Lars Wadsö, Building Materials, LTH
Mats Öberg, NCC Construction AB and Building Materials LTH
Lars-Olof Nilsson, Building Materials, LTH
Jonathan Karlsson, Building Materials, LTH
Anders Sjöberg, Building Materials, LTH

Summary

Within this project we have tried to clarify the importance of heat storage in heavy building parts, both when buildings are constructed and when they are remodelled. Constructing buildings today with this aspect in mind is a complex procedure and among other things includes increasing the energy efficiency, taking account of climate changes, and the transition to smart energy grids in order to obtain sustainable cities. We have chosen to present the work as a number of conclusions. Some of the factors you have to take into consideration when discussing heat storage in heavy buildings are the following:

- The traditional passive heat storage is sometimes completed with an active heat storage, which means that the building structure is used as a part of the heating system.
- The constructions sector today has to fulfil different requirements compared to yesterday and must today be seen as a part of a larger energy system. The present strive for energy efficiency, the on-going climate change and the development of sustainable energy systems and cities, with the help of e.g. smart energy grids, leads to that the importance of thermal inertia has increased.
- Smart energy grids imply a holistic view on the system for heating, cooling and energy consumption in sustainable cities. Such ideas are for example used in Kvillebäcken (Göteborg), Hyllie (Malmö) and Norra Djurgårdsstaden (Stockholm).
- Buildings with high thermal inertia decrease the power peaks and moves the power demand in time, which in the future can be optimized as an important part of smart energy grids.
- Not using excessive amounts of fuel by accelerating and breaking more than necessary is called eco-driving by the car industry. Eco-driving can reduce the fuel consumption with 10-20% compared to such a way of driving. A similar approach should be

applicable also to buildings. A consequence of this is that the indoor temperature should be controlled by indoor temperature sensors. There already exist several commercial systems for this.

- A review of existing commercial automation and control systems shows that there are fixed packaged solutions as well as programmable so called reference concepts available (from e.g. Siemens and Schneider Electric).
- The variation of the room temperature is surprisingly high over 24 hours even in buildings with high indoor comfort and with control towards constant indoor temperature. So high that the property thermal inertia is of importance.
- More energy efficient buildings and the on-going climate change lead to a higher number of hours with high indoor temperatures. The thermal inertia of the building has a significant imfluence for when cooling has to be installed in the future.
- If the power available for heating and cooling is limited the importance of the thermal inertia of the structure becomes considerably higher.

It is quite clear that constructing today is regulated by quite different requirements than only ten years ago, and that thermal inertia is a property which is (and will be) more and more focused on. At the same time the above described conclusions are not yet always quantified. Therefore the optimum use of them and their importance for better economy in the service stage of the building, lower use of fossil fuels, enhanced indoor comfort and increased robustness against climate changes are not known.

Introduction

Passive heat storage means that building parts with high heat capacity can absorb and emit heat when the temperature in the environment changes. This is a phenomenon that always takes place, even if no direct actions are carried out to utilize it at its full capacity. *Active heat storage* is when the structural parts of the building are used as a part of the heat system, for example by letting the intake air pass through holes in slab elements or by embedding the pipes of the heating system in the structure. With such systems the advantages of heat storage increase. Up to 20% reduced heating needs are mentioned.

When a building with a heavy structure is compared to one with a light structure, energy savings of about 4% are generally reported when all other building physical properties except the heat storage capacity are identical. These numbers are valid for passive storage and when the building is heated and cooled proportionally to the difference between the outdoor and indoor temperature. However, one should bear in mind that a high thermal inertia can sometimes be negative, as in those cases when a building is not heated or cooled constantly, as for instance in holiday houses or churches. As we are building more and more energy efficient buildings this difference remains a percentage, but decreases in absolute value.

One way to quantify thermal inertia is to calculate or measure the so-called time constant, which is defined as the time it takes for an object (a building in our case) to cool 63% of a final temperature drop, i.e. a kind of response time to a sudden temperature change.

Smart energy grids include production, distribution and use of energy that could handle all the users, sometime restricted to a local neighbourhood, and their needs and to attain sustainable and safe energy production. It encompasses a two-way communication from plants to connected devices to enable energy management. Smart grids were developed for electricity power supply grids. Today; the concept also includes other types of energy supplier systems such as district heating.

The knowledge about building thermal inertia has only developed to a small degree since the 1970-ies, which has led to that the validity in different special cases is discussed today. Within this project we have tried to clarify the importance of heat storage in heavy building parts, both when buildings are constructed and when they are remodelled. The results show that heat storage affects the energy consumption in form of reduced power peaks, better indoor climate and the form of the used primary energy. These are aspects that we believe will gain in importance in buildings and in the society in the future. At the same time, this is a very complex topic, and therefore we have chosen to summarize the work in a number of conclusions.

1. Modern constructing and sustainable cities must be looked upon in a holistic way

Constructing today has to fulfil other requirements compared to yesterday and must be seen as a part of a larger energy system. For instance, the following aspects have become more important for buildings of today and of the future:

- **Increased energy efficiency.** The energy consumption of buildings today is steadily decreasing. We know that increased energy efficiency to a great extent is based on a durable air-tightness during the buildings service life. We also know that increased heat insulation changes the moisture condition of the building envelope, which may turn well tried technical solutions into risky solutions. And we should not repeat former mistakes and let the energy efficiency be more important than the indoor comfort. Specifically, increased indoor temperatures have been focused on as a problem when energy efficient buildings are constructed.
- **Smart energy grids, both on the level of city districts and on a national level.** This means a holistic view on district heating, cooling and electricity, including treatment of the peak power demands of the system as well as environmental (e.g. CO_2) and economic impact from the selected energy source.
- **Climate changes** which leads to higher indoor temperatures and consequently an increased need for cooling.

2. The property thermal inertia becomes more important for modern constructing

Most buildings use more energy than anticipated from the beginning. Generally, this depends on that a building physics properties are overestimated, and that buildings are susceptible to errors in the production phase. However, it has been shown that the property thermal inertia is underestimated. Göteborg Energi has measured the rate of the temperature reduction in buildings when the heat supply has temporarily been closed down, and has found that buildings always have a higher thermally inertia than assumed. Never the less, the thermal inertia is not much used in automation and control strategies. Our work shows that the thermal inertia may affect several properties that are important for today's construction, such as indoor climate, energy consumption and power peaks, and that it should be an important component in future smart energy nets.

3. There is a large potential for automation and control systems for "eco-driving" of buildings.

Most automation and control systems used today are constructed to instantly compensate for the smallest of deviations. Transmission and ventilation losses are directly proportional to the outdoor temperature, which has led to that the heating and ventilation engineers develop automation and control systems based on this. The result is systems which try to give a constant indoor temperature based on the outdoor temperature. However, the thermal inertia of the building leads to that frequently the heating and/or cooling system are not in phase. Adjustments which take the dynamic behaviour of the building into account are only realized through so called “heat curves” (relation between heat load and outdoor temperature), which are mostly empirical and seldom optimal. Many existing automation and control systems are so complicated that they may obstruct the heat dynamic processes. In worst cases a building may be heated and cooled at the same time.

To control the building dynamically can be compared to what is called “eco-driving” of cars and trains, which in practise means driving with minimised fuel consumption. This means that one should not use excessive amounts of fuel by accelerating and breaking more than necessary, for example when higher motor power is used in an upwards slope to keep the speed constant. Eco-driving can reduce the fuel consumption with 10-20% compared to such a way of driving. A lot of energy is wasted if the accelerator is pushed in proportion to the slope of the road, irrespective of how long an upward or downward slope is, i.e. one disregards totally what the speed indicator is showing. But it is exactly this way a building is “driven” with traditional automation and control systems.

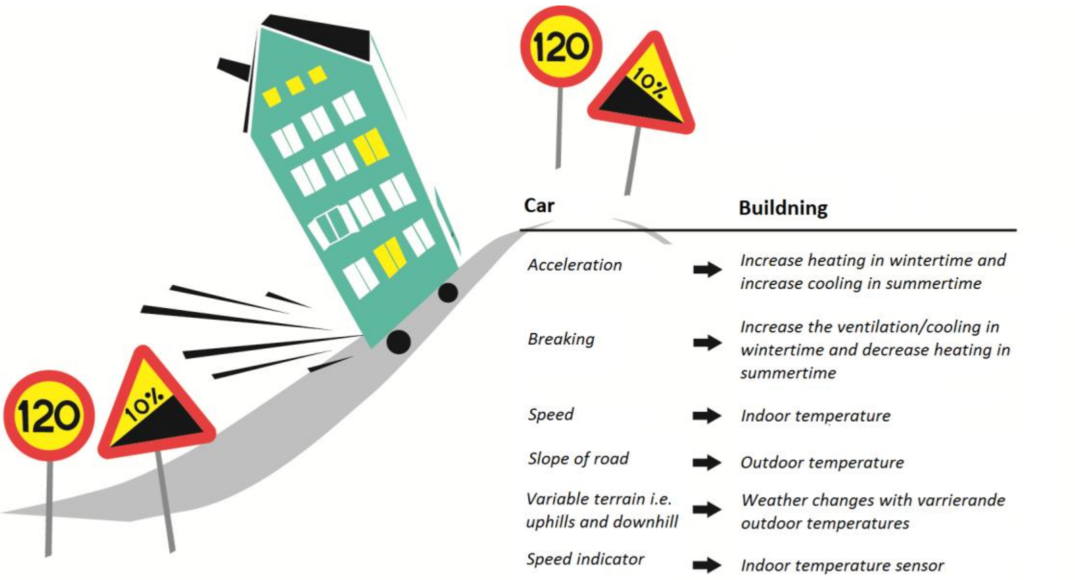

Figure 1: Analogy between car driving and heating a building

As the knowledge about the heat dynamics of buildings has matured and the prize on hardware to new automation and control systems has decreased, we have recently been given the possibility to control our buildings in an easy way in interaction with the basic heat dynamic law, and thereby decrease both peak power outputs and energy consumption. When reviewing the commercial products that use the thermal inertia of buildings we have found two types of systems:

- Packaged solutions with automation and control systems where heat dynamic algorithms are the core of the product.
- Reference concepts, which are delivered by Siemens and Schneider Electric among others.

Reference concepts are much more adaptable compared to the packaged solutions. These systems are programmable, which thus puts a large part of the responsibility on the persons that adapt the system for a specific building. How well the heat dynamic property is utilized may therefore vary considerably from one case to another. If this is well executed there is a lot to gain, but if this is handled in a wrong way it may in the worst of cases lead to that the building is heated and cooled at the same time.

4. The indoor comfort must be better controlled in the future

Previous studies of traditional buildings have shown that there is a large unexploited potential for heat storage in the existing building stock. One of the internationally most interesting studies has been made on buildings connected to the district heating system in Gothenburg. Indoor temperature in a number of existing buildings of various types (wooden houses, stone houses, low-rise, high-rise buildings) was measured, in order to assess the possibility of using them as heat storage (see Olsson Ingvarsson och Werner. “Building mass used as short term heat storage” in Proceedings of The 11th International Symposium on District Heating and Cooling. Reykjavik, Iceland, 2008). Based on presented measurement and findings in the article, it was found that:

- Most buildings have a high thermal inertia. Stone buildings can have time constants of 350 hours, but also wooden structures have time constants of about 100 hours.
- Most buildings have relatively large temperature variations during normal operation (positive from heat storage point of view), both over time (24 hours) and between different parts of the building. The reason for this is due to buildings thermostatic valves do not work ideally, and the lack of indoor temperature feedback to the automation and control system.
- The potential for the district heating supplier to use buildings as heat storage is very high.

Even if the intention is that the cooling and heating system shall maintain the indoor temperature constant, this is not obtained in practise. It is a myth that indoor comfort problems can be avoided if the heating system is designed to keep the indoor temperature constant. This myth often improperly disqualifies the use of the property thermal inertia for comfort reasons.

An alternative is to control the indoor climate dynamically with the help of the actual indoor temperature. In that way the heat dynamic properties of the building are automatically involved in the control. The important thing is that the variations of the indoor temperature are within well controlled limits. This is corroborated by the fact that building owners report an enhanced indoor climate when a traditional system has been replaced by a dynamically regulated automation and control system. If small temperature variations are accepted, such as 0.5 degrees celsius, a lot can be achieved. Moreover, there is also a possibility to decrease the medium temperature some degrees, since the indoor climate is adjusted within well controlled limits. It should be seen as natural that the temperature in a building varies somewhat.

When changing to a dynamic control strategy, one must take into account that what people experience of indoor climate is affected by many more factors than the measurable indoor temperature. Therefore actions have to be taken to eliminate errors in the building envelope, such as down draught close to windows.

There is a large risk that the need for cooling will increase in the future due to climate changes. In an article in the magazine “Energi & Miljö” the consulting company WSP predicts that the need for cooling will increase with 50% up to the year 2050. In our project we have studied the difference between a heavy and a light structure with regard to excessive temperatures. The climate scenarios we have used are taken from Rossby Centre, which is the climate modelling unit of the Swedish Meteorological and Hydrological Institute. The project has shown that there is a large difference in when cooling has to be installed in a building with a light structure (earlier) compared to a building with a heavy structure (later) when the same requirements on the indoor comfort are applied. For this reason new buildings which have many hours with excessive temperatures are in Denmark punished in the regulations even if cooling is not installed initially. In buildings with high thermal inertia future installation of cooling may be avoided or may at least be installed later.

In a part study in this project, where a simulation tool was used, the indoor temperature was allowed to vary somewhat by limiting the installed power, which gave considerably larger differences in energy consumption between a heavy and a light structure than if the indoor temperature was kept constant. To control the indoor climate only by limiting the installed power is of course a blunt tool, even though The National Board of Housing, Building and Planning (Boverket) uses this method for new buildings which are heated by electric radiators. This should therefore only be seen as an indication of the importance of the temperature variations.

5. The power demand is more important than the energy consumption

In addition to that the energy consumption (i.e. bought energy, kWh/m^2 and year) can be reduced somewhat when the thermal inertia of buildings is utilized, the power demand (W/m^2) may be highly affected since the thermal inertia may round off the power peaks and make it possible reposition the peaks in time. One might say that the owner, or the one who delivers the energy, may “deposit” or “borrow” heating or cooling from the structure instead of delivering heating and cooling “just-in-time”. This is particularly important when the energy demand is highest in other parts of the building or in the energy net. This is one of the bases in what are called smart energy grids of the future.

In a larger perspective the individual buildings are parts of the energy supply system of whole city districts, where the deliverer of the energy often alternate between production of district heating/cooling and electricity, depending on the actual power demand. In such energy supply systems there is a big need to be able to distribute the power demand over time, hour by hour. During certain periods of the day one would like to borrow power from the heating/cooling system and use this for heating of tap water or as electricity. In new city districts there are plans to introduce supply systems for electric cars and it will be necessary to distribute the energy use in an optimum way, so that houses and tap water are not heated at the same time as the cars are charged, especially during cold winter periods or warm summer days, and during the hours of the day when the need for warm tap water is at its maximum. The thermal inertia will in the future play an important role, since it makes it possible to reposition the power demand for electrical power in time. The thermal inertia of buildings is therefore an important factor in the development of what is called smart energy grids.

To clarify the importance of different energy sources different energy mixes are used as an example. The CO_2 emissions depends on the type of electricity used [source: www.energiradgivningen.se, Energi- & klimatrådgivningen]:

- Power suppliers electricity mix: 7,9 g CO_2/kWh
- Nordic electricity mix: 100 g CO_2/kWh
- Peak-load marginal electricity: 1000 g CO_2/kWh

Since the heating during very cold periods to a large extent is carried out with peak-load marginal electricity, large reductions of CO_2-outlets may be obtained by repositioning the power output in time. Hence, heavy structures have a larger potential to reduce the CO_2-outlets than light structures.

The energy used for production of district heating is distributed in a similar way. As an example the energy mixes of Göteborg Energi are shown in Figure 2 and 3.

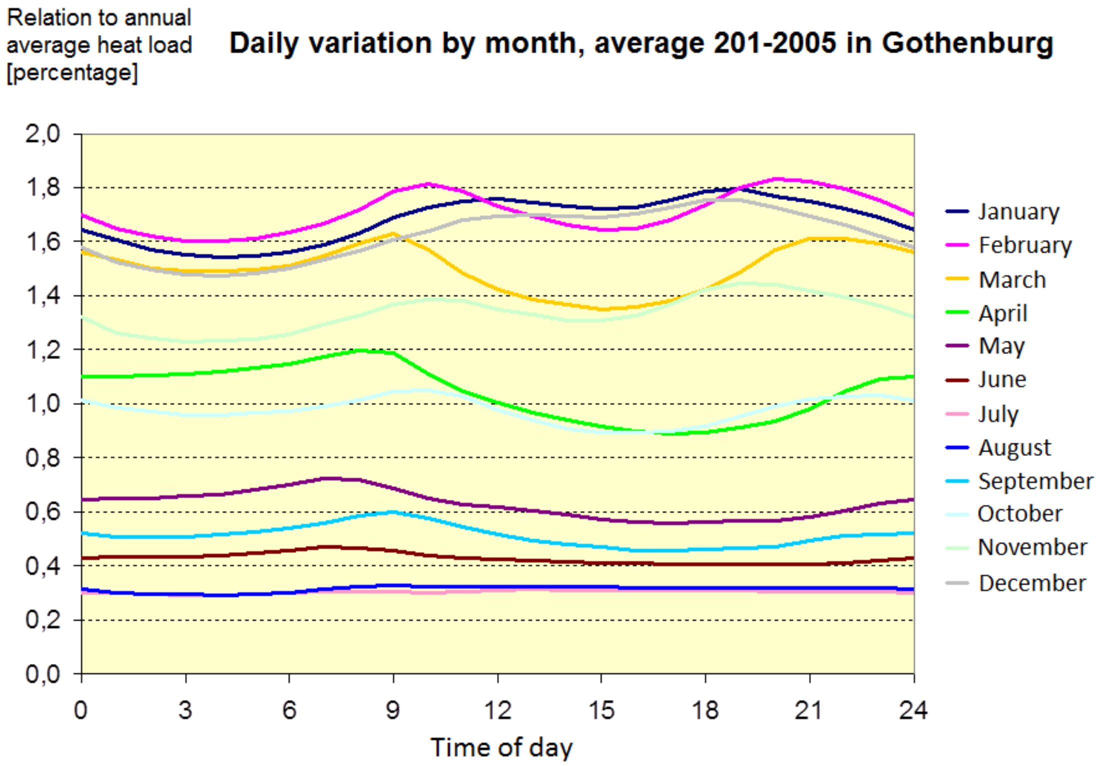

Figure 2: The diagram shows the variation in power output over the 24 hours of the day in the district heating net of Gothenburg. There are two power peaks each day, one in the morning and one in the evening. These peaks are due to an increased use of warm tap water. The difference between the maximum and the minimum power output is about 20%. The energy suppliers wish to eliminate this difference. In the figure it can be seen that the daily variations are largest during March and April, when the difference in outdoor temperature between day and night is large. Source: Göteborg Energi

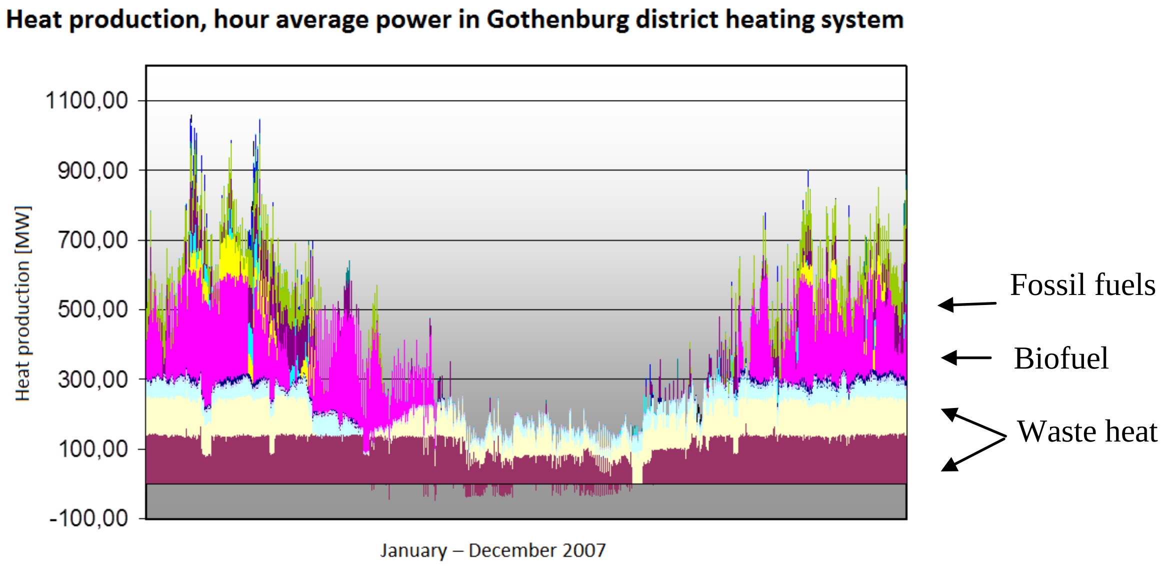

Figure 3: Variations in the need for heating during a year in the district heating system of Gothenburg (dark violet, white, light blue are waste heat; magenta is biofuels; yellow, green etc are different types of peak-power sources). The diagram shows the average value for one hour. Within a couple of days the values may vary over 100 megawatt depending on how cold it is outside and the time of the day. Source: Göteborg Energi

Both cost benefits and environmental benefits are at stake, since the amount of fossil energy sources used for production of hot water may be reduced. For the moment, it is necessary to use non-power producing boilers, i.e. boilers that do not simultaneously produce electricity, when the need for heating is at its maximum.

A prerequisite for reduction of the power demand is that there are a lot of buildings connected to the system. An individual building does not give any significant storage effect, but if thousands of buildings are parts of the storage system the joint benefit may correspond to that of a gigantic hot water tank. According to Göteborg Energi their development projects involving the use of buildings for energy storage are very promising, and they strive towards eliminating all daily variations in the future. In a first step the technique is tested in the new city district Kvillebäcken. Similar ideas about smart energy grids are tried for instance in the new city district Hyllie in Malmö, which is a cooperation between The City of Malmö, E-ON and VA Syd. Another example is the district Norra Djurgårdsstaden in Stockholm realized in cooperation with Fortum.

However, there is still a lack of consensus between the energy suppliers and the real estate business. While the energy suppliers are talking about primary energy and limitations of power demand (W/m^2) the real estate business only talks about energy consumption of bought energy (kWh/m^2) and indoor comfort. This barrier is not physical but mental. Therefore there is a need for encouragements for building owners to also consider primary energy and limitations of power demand. Since the concept “bought energy” does not reflect the emission of green-house gases the concept “primary energy” is more and more discussed. Also the use of fossil fuels as marginal energy source has a big influence, which makes it necessary to reduce the power peaks in our energy nets. This is one of the bases in the so called smart energy grids. The concept “bought energy” will remain even in the future, as an absolute minimum requirement for buildings, but the concepts “primary energy” and “limited power demand” should become at least as important also among building owners.

6. It is possible to improve the thermal properties of concrete

Concrete is the thermally heavy material we are primarily thinking of for buildings, but also stone and masonry have high heat capacities. We have in the project shown that there are possibilities to improve the thermal properties of concrete through phase change materials (PCM) and aggregates with high heat capacities or high thermal conductivity. However, such materials become considerably more expensive than ordinary concrete, so probably ordinary concrete will also in the future be the main material providing thermal inertia to buildings.
It is important that heavy materials in buildings are exposed so that the heat exchange can take place. They should be in contact with the indoor air if they are supposed to dampen the temperature variations, and they should be exposed to sun radiation if they are supposed to store free solar heating. They should not be covered by wallpapers, carpets etc.

To get an idea of how heavy building materials affect the heat use, the power demand and the comfort, simple models may partly be used. Such models can be very useful for conceptual discussions around energy systems for buildings.

Conclusion

It is important to utilize the thermal mass in a proper way. The energy consumption is not necessarily reduced only because there is a heavy structure, but the possibilities to reduce the energy consumption, lower the power demand and obtain better comfort is larger when there is a heavy structure to use.