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Chapter 5
Two Case Studies in Energy Efficient Renovation of Multi-family Housing; Explaining Robustness as a Characteristic to Assess Long-Term Sustainability

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Abstract. This study addresses two energy efficiency (EE) approaches to renovation of multi-family housing in Sweden aiming at a better understanding of robustness as a building characteristic especially in terms of energy performance of buildings and indoor air quality (IAQ). Gårdsten (Solar houses) and Brogården (passive houses) have been analyzed using an analytical framework. Adaptability, Redundancy, preference for passive techniques, users control over IAQ, transparency of systems to users and maintenance facility have been considered as the main criteria for robustness analysis and the performance of cases has been studied in relation to major factors likely to face uncertainties such as household appliances, occupant behavior, maintenance support, energy sources, technical systems, envelope quality and climatic conditions.

Keywords: Robustness, Energy efficiency, Sustainable buildings, multi-family housing, Renovation.

1 Introduction

1.1 Sustainable Development and Sustainable Building

According to the most often-quoted definition of sustainable development in The Brundtland Report, sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs... The concept by its definition encompasses a wide range of domains and thus many various fields of science. As it has been stressed by Roggema (2009), global warming and change of climate is likely to be the most critical problem of the 21st century. Tin (2008) explains that changes in the climate are happening faster and stronger than expected. This means that it is not possible to predict the future and we might face significant uncertainties. Thus, adaptation to changes seems inevitable. According to Roggema (2009), the best strategy is to get ready for facing the worst case scenario to be able to deal with probable serious changes in close future.

Sustainable building is a term which is usually used to stress the objectives of sustainable development in relation to building activities and the built environment

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(Femenías 2004). Since buildings are responsible for environmental issues such as CO2 emissions and consequently climate change, sustainable buildings are characterized partly by having less impact on the environment. However, the other side could be how well these buildings withstand the environmental conditions and adapt to future situations. Although there is no globally accepted definition for sustainable building as Femenías (2004) explains, for implementation of sustainable building it is suggested to consider several factors including a life-cycle systemic approach for different stages from planning to maintenance and even demolition of buildings in order to prolong the life span of the design and make it more flexible and adaptable. Thus, regarding sustainability in the field of architecture, buildings should be designed in a way that they are capable of dealing with unforeseen situations.

1.2 Problem Statement

Nowadays, there is a growing tendency towards strict energy consumption targets in building codes and energy efficiency standards (Simm et al. 2011). Thus, during the past recent years there have been efforts to design and build energy efficient buildings or renovate the existing housing stock into energy efficient housing in order to optimize buildings' energy consumption. Though in some cases the results have been reported to be satisfactory, in some other cases energy efficiency measures have been vulnerable to factors such as aging, maintenance requirements or user behavior etc.

The performance of some systems in a real life situation is not the same as their expected performance on the drawing board or in the test chamber (Leyten et al. 2005). This discrepancy between the predicted design performance and what will happen during the real life operation of a building can considerably influence the energy efficiency (EE) objectives of the building (Simm et al. 2011). Among other reasons, poor assumptions regarding the performance of the building and installations during modeling which can mislead the designers in their approach and occupant behavior could be mentioned as two commonly cited causes for such a performance gap (Simm et al. 2011 with refer to Raslan et al. 2009, Masoso 2009 and Torcellini et al. 2004). Gonzalez (2011) states that measures improving energy efficiency do not always result in the anticipated energy savings since part of the savings might be offset through other mechanisms. This phenomenon is referred to as the *rebound effect* in literature and energy efficiency debates and is partly caused by overestimating energy-saving potentials and underestimating saving costs. Such misestimation is mostly due to disregarding the impact of user behavior (Haas and Biermayr 2000). Especially if the use of any type of energy and natural resource or other inputs such as labor is considered, the system sometimes deviates from its efficient use of energy or economic objectives to a large extent. As for HVAC systems which are in a close relation to energy savings in a building, some factors including sensitivity to aberration from design assumptions, unfeasible maintenance requirements and lack of transparency to occupants and building management account for such vulnerability of measures and goals (Leyten and Kurvers 2005). Furthermore, technically sophisticated systems are more likely to be fragile due to their dependency on technology (Leyten and Kurvers 2005) and could easily affect energy efficiency of buildings. Consequently, in achieving sustainable architecture, energy efficient buildings which are dependent on sensitive measures are not desirable results, especially in a long-term perspective, and designers should plan for buildings with reduced vulnerability.

1.3 Methods

The approach undertaken in this study is based on qualitative methods. According to the explanation of Femenías (Femenías 2004), the process can be seen as abduction which is a kind of approach in between deduction and induction. According to the classification of Groat and Wang (Groat and Wang 2002), the methods used for this research are mainly literature review and case studies. However, since to collect data for case studies, different articles and brochures have been studied and methods such as interviews and study visits have also been conducted, it could be considered as combined strategies.

2 Robust Design

2.1 Main Concept

In a scientific approach, a correct understanding of a concept entails high perception of that concept which is not attained unless one is perfectly acquainted with its definition in that field of science, since considering just the lexical meaning, a word can be variously interpreted. Although there have been attempts to define concepts such as *Robustness* and *Robust design* in industrial science and the fields related to technical products or socio-technical systems, it seems there is still no comprehensive agreed definition for these terms in the scientific terminology. On the other hand, in some cases the term *Robustness* might be compared with conceptions such as *reliability*, *Durability* and *Dependability* on one side and *Stability*, *Resilience* and *adaptability* on the other side. Here the notion is investigated in two different but at the same time similar areas which would be related to the field of architectural design.

Robustness in Technical Systems (Andersson 1997). Andersson (1997) tries to clarify the difference between reliability engineering and robust design by providing the definitions of reliability, availability, durability and dependability and how they are all associated with the larger image of Quality. Eventually, Andersson formulates his definition of robustness in technical systems based on the model of technical process already presented by Hubka and Eder. Since the technical system is considered as the main operator of the technical process, the aim of robust engineering is to design systems in which unexpected secondary inputs cannot excessively affect the performance of the system and the result of the process. According to Andersson *If a technical system maintains a stated performance level of its properties in spite of fluctuations in primary and secondary inputs, the active environment, the operands and in human operation, then the system is robust* (Andersson 1997, P 282).

Robustness Engineering vs. Reliability Engineering. Andersson believes that the main difference between reliability engineering and robust engineering lies in the assumed conditions for the performance of a system. As the definition of reliability implies, reliability engineering deals with some anticipated conditions in a known environment including a set of usual expected variations, while in robustness engineering the system should be able to handle unusual unexpected situations and rare events.

Robustness in Socio-technical Systems (Pavard et al. 2006). In the article by Pavard et al. robustness of socio-technical systems is mainly studied by means of comparing the differences between *regulation*, *resilience* and *robustness* within the theoretical framework of complex systems. From this point of view three types of engineering for complex systems has also been presented; Classical engineering, resilience engineering and robustness engineering. *Intuitively, a robust system is one which must be able to adapt its behavior to unforeseen situations, such as a perturbation in the environment, or to internal dysfunctions in the organization of the system, etc* (Pavard et al. 2006, P 2). In order to better clarify the differences between these notions, three types of regulations are presented:

a) Classic regulations which aim to maintain a constant control over the behavioral variables of the system to guarantee the stability of the system's behavior.
b) Structural regulations which are able to adjust the structure of the system to the new situation by self-adaptation in order to preserve the function of the system.
c) Emergent and self-organized regulations that let the system to govern itself in an emergency situation by self-organization and in association with its environment.

This point of view for managing complex socio-technical systems is followed by introducing three required types of engineering:

1) Classical engineering which is characterized by functional stability and anticipating probable situations. This approach aims for *stable organization*.
2) Resilience engineering which is characterized by uncertain situations and reduced anticipation of the system's behavior. This approach aims for dynamic *reorganization.*
3) Robustness engineering which is characterized by emergent functionalities and no anticipation of further situations. This approach aims for *self-organization*.

Robustness Engineering vs. Resilience Engineering. As implicitly explained, the major difference between these two notions is that resilience engineering deals with undesired situations which are still possible to be anticipated and although changes might happen in the organization of the system, the aim is to preserve a certain result and keep the function of the system alive. This approach by its nature considers the system clearly separated from its environment. However, in robustness engineering, which deals with non-deterministic emergent situations in complex systems, firstly it is not possible to ensure that the function of the system or its subsets will be maintained and secondly the system is not assumed as a distinct entity since there might be a close interaction between the system and its environment and they could be tightly associated.

2.2 Robustness and Architectural Design

A building is a complex system, comprising several technical and socio-technical subsystems each of which might be subjected to the concept of robustness and could effectively influence the robustness of the whole system. Nevertheless to study robustness of a building as a set of interconnected systems there are major factors which could be generally considered in the design approach. These factors could be categorized as follows. However, since the focus of this study is on the energy efficiency measures, part 3 which is more relevant to this discussion will be further investigated.

1. *Robustness of building's physical structure*
-Main structure -Materials and installations
2. *Robustness of user's comfort and satisfaction*
-Indoor environmental quality -Functionality of spaces
-Aesthetic features
3. *Robustness of feasible operation and maintenance*
-Maintenance facility -Energy efficiency

Robustness of Maintenance Facility. Ease of care and maintenance of buildings is practically and economically influenced by design of details and implementation of different methods (Bokalders and Block 2010). IEQ of a building encompasses IAQ as well as thermal comfort, health, safety, quality of potable water and other issues such as lighting, acoustics, ergonomics and electromagnetic frequency levels. It would not be an exaggeration if one says that the success or failure of a building lies on its IEQ. To quote Chris Alexander (Brand 1994) more money should be spent on the basic structure and ceaseless adjustment and maintenance than on finishing. In order for robustness of facile maintenance and care in ecologically constructed buildings, they should be considered in the early planning phase. An important issue regarding maintenance of building services is that they should be easily accessible and adjustable as well as adaptable to new technologies and energy suppliers. According to Brand (Brand 1994) if the systems are too deeply embedded in the construction they cannot be easily replaced and this has caused many buildings to be demolished earlier than their efficient lifetime.

Robustness of Building's Energy Efficiency. Although the cost of energy in the future is still questionable, buildings with high energy consumption are very likely to be unacceptable in a few decades at least due to their ecological issues. Thus, it is of utmost importance that buildings are constructed with robust EE measures, since this will not only make their maintenance economically affordable in the whole building's lifetime but also prevent extra costs in the future to improve their efficiency by applying alternative solutions. According to researches done in Delft University of Technology (Linden 2007), regarding IAQ and EE, robustness of buildings can generally be improved through *user-oriented* and *climate-oriented* design approaches. Considering the definition of robustness, EE measures in a building should be insensitive to changes in the situation or the active environment. In their article, Leyten and Kurvers (2005) refer to the definition of robustness of a technique in statistics which is *the ability of a certain technique to deliver accurate results, although its assumptions are violated* and analogously formulate a definition for robustness of a building and an HVAC system as *the measure by which the building or the system lives up to its design purpose in a real life situation.* Furthermore, in a comparison between low-tech and high-tech solutions, less technically complicated buildings are often more robust (Leyten and Kurvers 2005). This means that the measures should not be dependent on sophisticated technical solutions. Juricic (2011) explains that complex building systems such as mechanical ventilation or active cooling systems are very likely to cause high energy consumption or lack of thermal comfort to users due to lack of transparency which leads to misuse. Moreover, experiences indicate that people would prefer buildings without cooling but with operable windows to those with fixed windows and cooling systems and they even accept temperatures higher than the comfort range in the former case (de Dear et al. 1997). Leyten et al. (2009) stress that user control over IEQ such as control over natural ventilation, temperature, sun shading and artificial lighting increases robustness of buildings. This is because users get the opportunity to adapt IEQ to their specific personal preferences and probable malfunctioning of the building will be compensated. Juricic (2011) points to *redundancy of systems and multiplicity of functions* as a building characteristic which helps its robustness. Sussman (2007) has developed a metaphor explaining such a concept in natural systems such as in human body where several functions are fulfilled by different organs or some other organs might be adapted to achieve the goal in case of failure in the main organs. According to Juricic (2011) *one system, several functions* would be the worst case while *several systems, one function* could be considered as the best case.

3 Case Studies

For this study two cases have been selected which are both well-known demonstration projects of multi-family housing renovation in Sweden. Gårdsten in Gothenburg and Brogården in Alingsås have been retrofitted both with the main focus on the energy performance of the building but with two different approaches to energy efficiency.

3.1 Solar Houses, Gårdsten, Gothenburg

Solar houses1 (Solhus1) is the renovation of 255 apartments comprising 10 buildings (3 high-rises and 7 low-rises) in West Gårdsten which was initiated at the time for the call for targeted projects for the THERMIE program in 1996 (Dalenbäck 2007). The renovation project started in early 1998 and was finalized in 2001.

Energy Efficiency Measures. In the high-rises, the original flat roofs have been covered by extra insulation on top and a shed roof facing south with integrated solar collectors for preheating domestic hot water was added on top of the building. In each block, storage tanks have been placed in the basement of 6-story building and pre-heated water (heated almost 35% by solar energy) is stored there to be distributed to all the apartments and the common laundry in the block. The supplementary heat is provided through district heating system. Furthermore, the previous open balconies to the south have been repaired and enclosed with glazed panels. The apartments are supplied with fresh air preheated by sunlight through these glazed balconies. Fresh air enters the living rooms and bed rooms adjacent to these balconies through air inlets designed in the windows and balcony doors. The exhaust air is directed out from the existing exhaust system in kitchens and bathrooms on the northern part of the flats (Dalenbäck 2007). Despite of low investment incentives for insulation of all external walls due to low energy costs, the gables in the high-rise buildings were insulated. Existing laundry rooms, located in the basement of the high-rises were replaced with new laundry rooms, designed in the ground floor of these buildings. The new laundries were equipped with energy efficient washing and drying machines, connected to the domestic hot water system in the basements to save electricity for water temperatures below 50°C. Moreover, communal greenhouses have been built on the ground level of these buildings, adjacent to the new laundry rooms along more than half the length of the building to the south. In all buildings the inner window panes of the existing double glazed windows have been replaced with new low-emission panes (Dalenbäck 2007). All apartments have been equipped with energy efficient household appliances and all households have been provided with individual metering systems for water, electricity and space heating in their flats (Nordström 2005).

However, in the low-rise buildings the existing ventilation systems were equipped with a heat recovery installation and the flat roofs were covered by external thermal insulation. One of the low-rises has a unique design in this project. The external walls to the east, north and west of this building have been covered with an extra layer of thermal insulation and a cavity has been created between the original walls and this new layer. These walls are not only protected from outdoor cold weather but also warmed up by circulation of heated air in this gap. The air is heated through solar collectors vertically installed and integrated to the southern façade of this building (Gårdstensbostäder 2010).

3.2 Passive Houses, Brogården, Alingsås

Brogården consisted of 299 apartments in sixteen 3-story buildings originally constructed in the early 1970s as part of *the million homes program*. As the first experience of retrofitting with passive house techniques in Sweden, the renovation process started in March 2008 and the whole project is to be completed in 2013 (Morrin 2009).

Energy Efficiency Measures. The main idea behind passive house concept is making heat losses as less as possible. This technology involves sufficient insulation for building envelope as well as making it as air tight as possible. In such a system not much energy is needed for space heating and the air inside the building would be sufficiently warmed by the heat from occupants' body, household appliances etc. In order to provide fresh air in such airtight spaces, the buildings are equipped with heat recovery ventilation systems of high efficiency.

In Brogården the external shell of the buildings was highly insulated. The ground slab was insulated with a total thickness of 200 mm of EPS on both sides. The exterior long side walls which were in a poor condition were replaced with newly built walls with a steel structure and layers of mineral wool and EPS (app. 440 mm) and the insulation layers on the attic floor were replaced with 400-550 mm of loose wool insulation (Morrin 2009). All windows and entrance doors were replaced with xenon gas-filled triple glazed thermo windows and highly insulated doors respectively. The existing recessed balconies which made substantial thermal bridges in the external walls were enclosed as part of the apartment interior space and new balconies were built, standing on a separate structure and mounted on the outside of the façade (Janson 2009). The previous ventilation system was replaced with air-to-air heat exchanger units with 85% efficiency (Janson 2008) installed in each apartment. In very cold days (estimated app. 10 days a year) (Eek 2011), these units can also provide the incoming air with extra heat from the district heating system. The air inlets have been mounted on the living rooms and bedrooms walls and the out lets are in the kitchens and bathrooms. The apartments have been equipped with low-energy household appliances. Almost 60% of the apartments will be accessible by low-energy elevators which store energy from downward motions to be used in upward motions (Morrin 2009).

4 Analysis

In this part the cases are analysed based on the criteria of robust design with regard to changes in some major factors affecting building's energy performance (Table 1). According to our studies robust design deals with reduced vulnerability to any unforeseen situation and thus a thorough robustness analysis entails a comprehensive study of future circumstances. However, among different factors influencing energy efficiency, some of them seem to be more essential and more likely to face uncertainties during building's lifetime including:

- **Household appliances** (using new appliances due to different lifestyles etc.)
- **Occupant behavior** (unexpected patterns of energy consumption)
- **Maintenance support** (Changes in building management etc.)
- **Energy sources** (Introducing different energy supplies due to cost etc.)
- **Technical measures** (issues related to availability of sophisticated systems)
- **Envelope quality** (physical changes due to issues such as aging)
- **Climatic conditions** (issues such as global warming etc.)

Furthermore, among other criteria, adaptability of systems, redundancy of measures, preference for passive techniques and user-oriented design criteria such as users control over IAQ, Transparency of systems to users and facility of maintenance have been chosen as the main robustness criteria for the analytical framework. Since EE buildings are characterized by focusing on three major issues of user comfort, environmental impact and energy cost, the relation between these issues and the aforementioned factors and criteria has been presented in the following diagram (Fig. 1).

While regarding heat loss and energy saving, passive housing seems to be a safer solution due to highly insulated and well air tight envelopes, both cases could be at risk of energy performance reduction in case of unexpected situations in their life time. What seem to be common in both projects are issues related to availability of technical systems, redundancy of systems and feasibility of maintenance. In case of technical solutions such as solar panels, ease and cost of maintenance, as well as availability of the technique and its performance in relation with environmental factors can be questionable whereas energy efficiency in a long-term perspective through passive house method which is quite dependent on building fabric and details, could be vulnerable to issues such as performance loss of thermal insulation materials.

Although the criteria for robust design have been presented with the same level of significance in this table, it is possible to determine more effective factors and criteria by applying methods such as system design to find the leverage points of applied systems according to the specific characteristics of each project.

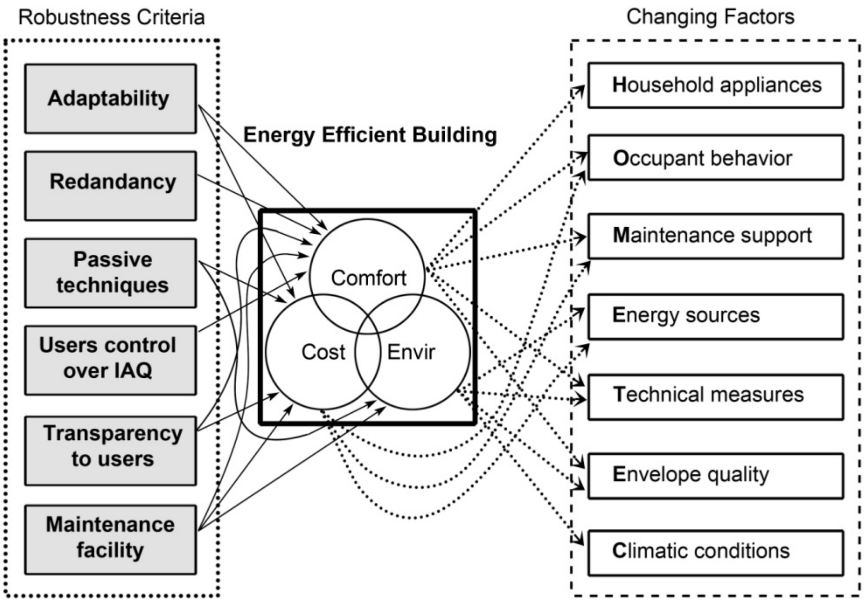

Fig. 1. Relation between main objectives of EE building, robustness criteria and HOMETEC factors

Table 1. Analysis of the cases based on the criteria of robust design and major factors of change[1]

		Gårdsten	**Brogården**
Robust design criteria	**Adaptability of systems**	+ Glazed balconies adaptable to different outdoor climates (C),(O) - Technical issues of adapting preheating/heating systems to alternative energy sources (ES),(M)	+ Façade material can be easily replaced (C),(O) - Economic issues in case of performance loss in insulation material (EQ),(M)
	Redundancy of measures	+ Possible use of electricity based systems for heating/cooling (C),(O) - Alternative heating/cooling devices not provided in the apartments (O),(H)	+ Possible use of simple sources of energy such as candles for space heating due to highly insulated and air tight envelope (ES) - Lack of fresh air in case of failure in heat exchanger (T),(M)
	Preference for passive techniques	+ Preheating of incoming air through glazed balconies in high-rises (C) + Solar gain through larger windows in living rooms facing south (C) + Sun shading provided both by balconies and operable blinds and curtains (C) - Considerable heat loss through building envelope (C),(T) - Apartments not very well air tight (C),(T) - Heat loss through entrances in the open balconies with no air lock (High-rises) (O),(C)	+ Highly insulated building envelope (C),(T),(EQ) + Xenon gas-filled triple glazed windows (C),(T) + Well air tight apartments (C),(T),(EQ) + Solar gain through larger windows in living rooms facing south, east or west (C) + Sun shading provided both by balconies and operable curtains (C)
	Users control over IAQ	+ Operable windows (C) + Operable glazing panels in balconies (C) + Adaptable indoor temperature (O) + Blind curtains to control daylight (C) - Possible unnecessary use of glazed balconies with extra heating in cold days(O),(H)	+ Operable windows (C) - Integration of heating and ventilation (T)

[1] (H): Household appliances, (O): Occupant behavior, (M): Maintenance support, (ES): Energy Sources, (T): Technical systems, (EQ): Envelope Quality and (C): Climatic conditions.

Table 1. (*continued*)

	Transparency of systems to users	+ Radiating panels used for heating (T),(M) + Glazed balconies to preheat incoming air (T),(M) - The system of solar panels to preheat hot water not easily understandable for layman (T),(M)	+ Highly insulated building envelope + Air tightness of the spaces (T) - Mechanical ventilation and integration with heating (T),(M)
	Facility of maintenance	- Technically sophisticated parts such as solar panels preheating water or heating air in the low-rise building facing south not very easy to maintain (T),(M)	+ The buildings dependent only on one technical system (heat exchanger) which has only a filter to be changed per year (M),(T) - Constant need for technical maintenance (T),(M)

5 Conclusion and Further Remarks

This study aimed at a better understanding of robustness as a building characteristic, especially regarding energy efficiency measures, IEQ and users' comfort. The study indicates that robustness is a qualitative characteristic of systems, specifically buildings in this research, which is generally defined as *the characteristic of measures by which the building or the system lives up to its design purpose in a real life situation*. Consequently, this characteristic is closely related to adaptability of a building and its subsystems. Particularly, for multi-family housing, design for *robustness* seems to be a characteristic which can enhance building *sustainability* from different points of view and support the functional purpose of buildings. Since both notions aim for more durable and reliable systems, design for robustness is quite in sync with sustainable architecture. Therefore, the concept could be applied to assess sustainability of design in a long-term perspective. According to this study robustness of a building and particularly multi-family housing, can be noticeably enhanced through *user-centred* and *climate-oriented* design approaches. These two approaches provide the designers with more comprehensive data to have more realistic predictions and prevent inaccurate assumptions and misestimation of design performance during modelling.

According to the case analysis, there are major factors influencing building's energy performance in a long-term perspective which should be analyzed in the design process in order to assess robustness of design and building's sustainability. These factors which are likely to face unforeseen situations during building's lifetime include: *household appliances*, *occupants behaviour*, *maintenance support*, *energy sources*, *technical measures*, *envelope quality* and *climatic conditions*. On the other hand, aiming for a building with robust energy efficiency measures entails a design process with accurate assumptions in which criteria such as *adaptability*, *redundancy*, *preference for passive techniques*, *users control over IAQ*, *transparency of systems to users* and *facility of maintenance* are taken into account.

An important point of the study to be stressed is that sometimes aiming for a robust design does not necessarily mean to achieve the most efficient performance of the building, especially in a short term perspective. For instance, regarding energy efficiency of a building, some measures seem to save more energy and thus more efficient, but concerning user comfort they are unsatisfactory, likely to cause unexpected behaviours and thus not necessarily robust. Therefore in evaluation of a design or deciding for design characteristics, robustness and efficiency should not be misinterpreted.

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