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In the business of building green:

The value of low-energy residential buildings from customer and developer perspectives

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Doctoral Thesis

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Abstract

An overarching aim of this research was to investigate the comprehensive value of green residential buildings as seen from two perspectives: that of the developer and that of the occupant (the customer). The dissertation consists of studies presented in seven papers. The studies conducted to investigate the developer's perspective focused on construction cost and potential profit (papers I and VII). The customer's perspective was examined with three approaches: the impact that energy and environment have on the decision to purchase (or rent) an apartment (paper V), willingness to pay for a green apartment (paper VI) and finally, the occupants' satisfaction with the dwelling and indoor environment (papers II, III and IV).

The first paper examines whether increased investment costs are profitable, taking into account the reduction in operating costs. The investment viability is approached by comparing investment in conventional and green residential building, particularly passive houses, using real construction and post-occupancy conditions. The increased investment costs in energy-efficient building were also the focus of paper VII. In this paper, the aim was to study how technologies used in energy-efficient residential building construction affect the available saleable floor area and how this impacts on the profitability of the investment. Potential losses and gains of saleable floor area in energy-efficient buildings were assessed using a modelled building and analysed with the help of the average construction cost.

Papers II and IV present results from a study of occupants' satisfaction and indoor environmental qualities. Both papers aim at comparing and analysing responses from occupants living in green and conventional buildings. Paper III focuses on a similar subject, but investigates occupants' satisfaction among all adults living in multi-family buildings in Sweden, providing a national context for the results presented in papers II and IV. The results indicate that occupants are generally satisfied with their dwellings, but indoor environment proved to have a statistically significant effect on overall satisfaction.

The results in paper V indicate that energy and environmental factors have a minor impact on customers' decision to purchase or rent an apartment. However, availability of information on building energy and environmental performance may have an effect on the likelihood of the buyers' being interested in environmental qualities and consequently an impact on their decision. The study presented in paper VI shows that customer interest in energy and environmental factors has a significant impact on stated willingness to pay for green dwellings. The paper discusses the stated willingness to pay for low-energy buildings and buildings with an environmental certificate and attempts to assess the rationale of the stated willingness to pay for low-energy dwellings given potential energy savings.

Keywords: sustainability, green buildings, residential buildings, low-energy, energy-efficiency, construction cost, profitability, occupant satisfaction, indoor environment quality (IEQ)

Abstrakt

Fokus i detta forskningsprojekt har legat på att undersöka värdet av gröna bostäder ur ett brett perspektiv, dvs både genom att studera byggherrens och de boendes (kundens) synpunkter. I avhandlingen ingår sju uppsatser. Undersökningen av byggherrens synpunkter fokuserades på kostnader och potentiella inkomster (uppsats I och VII). Kundernas åsikter undersöktes på tre olika sätt: vilken effekt energi och miljö faktorer hade på beslut att köpa eller hyra en lägenhet (uppsats V), betalningsvilja för gröna bostäder (uppsats VI) och slutligen de boendes trivsel samt nöjdhet med inomhusmiljön (uppsats II,III och IV).

Den första uppsatsen syftar till att undersöka om ökningen av investeringskostnader vid byggande av gröna byggnader kan täckas av framtida energibesparingar och minskning av driftkostnad. Investeringens lönsamhet undersöktes genom att jämföra skillnader i byggkostnader mellan konventionella och gröna bostäder med skillnader i driftskostnader givet olika antaganden om energipriser och räntekrav. Huvudfokus i uppsats VII var också byggkostnader, men denna gång undersöktes hur nya tekniska lösningar påverkar boarea och lönsamhet av energieffektiva bostäder. Genom att konstruera en modell av ett typhus analyserades potentiella ökningar i boarea med nya lösningar och hur detta påverkade lönsamheten i olika geografiska lägen (prisnivåer).

Uppsatserna II och IV presenterar resultat från boendeundersökningar. Båda uppsatserna syftar till att undersöka boendes trivsel och nöjdhet med inomhusmiljö samt att testa skillnaden i svar från boende i gröna och konventionella bostäder. Uppsats III fokuserar också på inomhusmiljön, men analysen gjordes på svaren som samlades in under *Boverkets projekt BETSI* och resultaten är därmed representativa för alla vuxna som bor i flerfamiljshus i Sverige. Uppsats III ger därmed en national kontext för uppsatserna II och IV. Resultaten visar att boende trivs i sina bostäder, men inomhusmiljön har en statistiks signifikanta effekt på allmän nöjdhet faktor..

Resultaten i uppsats V tyder på att energi- och miljöaspekter spelar mindre roll i beslutet att köpa eller hyra en lägenhet. Den synliga informationens tillgänglighet angående byggnadens energi- och miljöprestanda, påverkar kundens intresse för dessa faktorer och därmed indirekt hushållets beslut. Resultaten i uppsats VI pekar på att kunderna, som är intresserade av byggnaders energi och miljö prestanda, är villiga att betala mer för gröna bostäder. I uppsats 6 diskuteras betalningsvilja för låg-energi byggnader och för byggnader med miljöcertifikat samt utvärderas om den angivna betalningsviljan är rationell beslut när man tar hänsyn till nuvärdet av framtida energibesparingar.

Nyckelord: hållbarhet, gröna byggnader, bostäder, låg-energi, energieffektivitet, byggkostnad, lönsamhet, boende nöjdhet, inomhusmiljö

Acknowledgement

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Tyresö, September 2013

Contents

1. Introduction

The existing policies and regulations are directing companies towards adopting a more environmentally conscious path for business operation. One example is the European Directive for Building Performance from 2002 (directive 2002/91/EC) and later re-cast in 2010 (directive 2010/31/EU), which has sculptured the future of the building industry for many Europeans countries. From a developer perspective, it might be wise to add a “green element" to the company strategy, as it might be a way to adapt to the future market conditions.

However, the fact that regulations propel applications of energy-efficient solutions in building construction does not demonstrate the investment feasibility of green buildings. Would developers lose or benefit by building green? Do customers care? Do customers value the environmental elements while purchasing an apartment? This thesis attempts to answer these questions and assess a comprehensive value for green buildings.

1.1. Aim and research questions

Considering climate change policies, high emission (Co2) levels, energy prices and financial market crises, the pressure on the construction industry has never been greater. However, as part of adjusting to change, a company must keep stakeholders satisfied and make a satisfactory profit.

The profit, however, should not be considered as an ultimate goal; it is rather a consequence of delivering a value to customers and therefore defined as the difference between a price that customers are willing to pay and the cost of performing activities involved in creating the product (Porter, 2008). From the long term perspective, high profit is achieved if the value delivered to the customer is the same as the value perceived by the customer (Aaker, 2001; Porter, 2008).

The intention of this thesis was to investigate comprehensive value of “green” residential buildings as seen from two perspectives: that of the developer (the company) and of the occupant (the customer). I believe that the focus in any business should be on the customer. It is the customer who allows the company to generate the income. It is the customer who is willing to purchase a dwelling for the price that allows the company to make a profit. It is the customer who makes the final judgement of whether the goods have attained the level of satisfaction. In the case of apartment purchase, satisfaction may be impacted by various factors, for example the perceived quality of the apartment (building), satisfaction with indoor and outdoor environment (even neighbourhood) or a profit made at the point of sale of the apartment.

If we simplify, the developer’s profit depends on the income and the construction costs. The company may decide to differentiate from its competitors, for example, by building green instead of conventional building, if this strategy contributes to higher value. There are reasons to believe that green building has the potential to present better living quality for occupants in the form of better indoor environment, reduced requirement for energy and low environmental impact. The choice of building green may be profitable if the above-mentioned qualities are perceived as important by the customers, and if they are willing to pay more for green dwellings.

Following this reasoning, the objectives and research questions in this thesis were to:

- Discuss potential barriers to and opportunities for high-performance green building development
- Explore the cost difference between construction of conventional and low-energy green building
- Investigate investment potential and factors contributing to the profitability of green residential buildings
- Investigate the importance of environmental factors in customers' decision to purchase or rent an apartment
- Study occupants' willingness to pay for green buildings
- Explore customers' perceived product value by investigating occupants' overall satisfaction
- Study the delivered value of products as perceived by customers by investigating occupants' perceived satisfaction with indoor environment quality

In the further part of this chapter, I discuss different terms describing buildings designed and constructed with environmental goals, notions that often appear in the literature and practice (section 2). In this section, I attempt to array concepts and lay out the relationship between them. I also specify the practical definition of "green" buildings used in this research. The third section I devote to the general research method applied in this thesis and discuss some limitations and potential bias. In the fourth section, I briefly summarize the papers included in this thesis and the chapter ends with overarching conclusions and suggestions for further research (section 5 and 6 respectively).

2. Definitions

Buildings that are designed and constructed to minimize environmental impact are often referred to as "sustainable buildings", "green buildings", "low-energy", "energy-efficient" or "high-performance", "passive house " and "(nearly) zero energy buildings". Sometimes it is safe to use them as synonyms, but sometimes similarities are vague. This section aims to review definitions proposed in the literature and attempts to capture differences and similarities between the above-mentioned notions.

2.1. Sustainable building

Sustainable development (sustainability) in its core focuses on the importance of responsibility for present actions and for future generations (WCED, 1987). The goal is to combine best practice from economic, social and environmental aspects. The strategies for defining and achieving sustainability goals may vary depending on people's beliefs and expectations, political aspirations and even economic status. Consequently, contextualizing sustainability in buildings has proved to be challenging.

The sustainability goals may be defined at a specific point in time, hence making the aims reachable, but in the long term perspective sustainability changes, evolves, is adapted to the new status and therefore achieving sustainability goals should be seen as a continuous process of transformation (Bagheri and Hjorth, 2007; Berardi, 2013). This "metamorphosis" and the three-dimensional (economic, social and environmental) nature of sustainability (Kohler, 1999) are fundamental for sustainable development, and separation of these domains can lead to mistaken conclusions. Kohler (1999) explains that sustainability, if applied in the built environment, must still be described in three unbreakable frameworks, where ecological sustainability aims to protect resources and ecosystems, economic sustainability is divided into investment and running costs, and social and cultural aspects refer to comfort, wellbeing and the protection of human health.

The multi-dimensionality of sustainability, the variation in goals depending on time, location, circumstances and actors involved contributed to the many ways in which the concept of sustainability could be defined. Berardi (2013) recaptured discussions on sustainability and used CIB's ten redefined principles for sustainable building and principles reported in the Sustainable by Design Declaration of the International Union of Architects to define sustainable building as:

> *"A healthy facility designed and built in a cradle-to-grave resource-efficient manner, using ecological principles, social equity, and life-cycle quality value, and which promotes a sense of sustainable community. (..) a sustainable building should increase:*
>
> - *demand for safe building, flexibility, market and economic value;*
> - *neutralization of environmental impacts by including its context and its regeneration;*
> - *human wellbeing, occupants' satisfaction and stakeholders' rights;*
> - *social equity, aesthetics improvements, and preservation of cultural values"*
>
> (Berardi, 2013)

However, the multi-dimensionality of sustainability and the complexity of building systems created a trap which many sustainability assessment systems have fallen into (see for example Reed et al., 2009; DeLisle et al., 2013). Capturing all the aspects of sustainability and setting measurable goals might be impossible to achieve or could result in an assessment tool that was far too complex to use. This may explain why assessment systems focused on environmental aspects evaluated during the time-limited designing and construction phase, and rarely considered the whole life-cycle stretching to operation and in-use assessment. There have also been voices that questioned the possibility of fulfilling all sustainability aspects (Goodland and Daly, 1996; Williams and Millington, 2004; Cooper, 1999; Pearce, 2006).

2.2. Green Building

A Google search for "green building" gives over 1,740,000,000 hits and "green building definition" appears on 65,800,000 sites. Generally, the term is often used in relation to buildings constructed with more ambitious environmental goals than in conventional buildings.

Kibert (2008) defines a "green building" as: *"a healthy facility that is designed, built, operated and disposed of in a resource-efficient manner using an ecologically sound approach*". The term "green building" gained its popularity mostly due to the efforts of various agencies, organizations and councils that are successfully promoting this concept. The U.S. Environmental Protection Agency (www.epa.gov) states that “green buildings are designed to reduce the overall impact of the built environment on human health and the natural environment”. This is achieved by efficient use of resources, occupant health protection and reduction of waste and pollution. Nowadays, there are many organizations and programmes which aim to promote ”green” or “sustainable” building concepts, e.g., the World Green Building Council (www.worldgbc.org), the U.S. Green Building Council (www.usgbc.org), the Swedish Green Building Council (www.sgbc.se) and the GreenBuilding Programme (GBP) initiated by the European Commission (www.eu-greenbuilding.org).

A “green” building may have different levels of “environmental involvement” or “shades of green” from so-called “light green” to “deep green” (Cole, 1999). The “light” level includes highly efficient choices like energy-efficient lighting, whereas “deep green” refers to more demanding commitments (e.g. regarding design or financial inputs) such as choice of environmentally accepted materials or implementation of solar energy collectors.

The fundamental objective of a “green” environmental assessment method is to promote designing, constructing and owning buildings with improved environmental performance (Cole, 1999). There are differences between the “green” assessment method, which is based on relating the building to a “typical” practice without defining an ultimate goal, and the “sustainable” method, which should assess the building against declared (locally and globally) sustainable conditions (Cole, 1999). The difference between concepts of green and sustainable building was discussed by Berardi (2013).

In practice, the general rule is that in order to be labelled a “green” or “sustainable” building, it must comply with specific standards and their environmental impact must be assessed. Numerous assessment methods have been developed all over the world. The most known and commonly used are: LEED (origin US), BREEAM (origin UK), Green Star (origin Australia), and CASABEE (Japan). To-date, almost every country has introduced an environmental assessment method, either newly created methods, or modified or adjusted versions of earlier established systems (e.g. LEED India). Building assessment and certification is a process. Assessment is carried out against specified criteria and points are awarded for complying with specified standards. Finally, the total number of points indicates the level of building performance.

Environmental assessments promote environmental awareness, but also provide a framework for the work of professionals and opportunities for certification and labelling of buildings even in in compliance with governmental policies (Reed et al., 2009). Each rating system has certain advantages but also some shortfalls. The greatest problems are lack of transparency and the difficulty in rating comparisons (Reed et al., 2009). The reasons for this are that each assessment method is more or less tailored to the country of origin with reference to general rules, construction standards or climate conditions. Moreover, various assessment methods address different criteria or assign to them different weight.

Some building environmental assessment methods try to capture the complexity of a building and therefore tools include rather a long list of criteria, making the assessment quite complex. This complexity is another criticism against rating tools. Since there are quite a number of factors where building may score points, some of the areas (sometimes important ones like energy or material) may be left aside, but the final score may still be high.

2.3. Energy-efficient building

Building life cycle is counted as 50-100 years and during this time the total energy associated with a building may be divided into energy that is directly connected with the building itself-- energy needed for the building's construction, operation, rehabilitation and demolition, and embodied energy, which is the sum of all energy needed to manufacture and transport goods (all material and technical installations) (Sartori and Hestnes, 2007). The question of how embodied energy and operating energy influence the total energy used in a building's life cycle is the subject of discussion in the literature. Results differ depending on building type, production year, climate zone and finally energy measures used to analyse a building's performance. Energy used in buildings can be expressed in end-user energy or primary energy. The primary energy measures energy at the natural source level, and indicates energy needed to obtain the end-use energy, including extraction, transformation and distribution losses (Sartori and Hestnes, 2007) focusing on energy resources and the process in the supplying system. Hence, two different buildings may indicate the same end-energy performance but differ significantly in performance measured in primary energy, due to different energy sources (Gustavsson and Joelsson, 2010).

2.4. Low-energy building and the passive house concept

Low energy and the passive house concept essentially build on the same idea, that the heating energy in the building can be minimized through an airtight and well insulated building shell. However, whereas the former is rather a guideline and rarely specified in practical values (e.g. heat load or space heating minimum), passive house is a standard and gives specific recommendations with regard to the achievement of heating energy savings.

2.4.1. Low-energy building

It is generally understood that a low-energy building should achieve better or significantly better performance values than those specified in the Building Regulations. The supply of energy needed for heating/ cooling can be decreased only if the energy losses can be minimized. The energy leakage can be reduced by minimizing thermal bridges, including very good thermal insulation for the whole building envelope (very low heat transfer coefficient values for walls, foundations and roof), and energy efficient windows. In order to achieve good indoor comfort, an appropriate ventilation system should be installed (Krope and Goricanec, 2009).

There are some definitions of low energy buildings. In Switzerland, for example, low energy buildings are promoted by the non-profit organization MINERGI®. MINERGI® is registered as a "quality label for new and refurbished buildings"." MINERGI-Standard" requires that buildings "do not exceed more than 75% of the average building energy consumption and that fossil fuel consumption must not be higher than 50% of the consumption of such a buildings" (www.minergie.ch).

The Forum for Energy-efficient Buildings (*Forum för energieffektiva byggnader* - FEBY), the organization that promotes building and renovation to energy-efficient standards in Sweden (www.energieffektivabyggnader.se), was the first in Sweden to officially recognize two types of low-energy houses: passive house and mini-energy house (Forum för energieffektiva byggnader, 2009a, Forum för energieffektiva byggnader, 2009b). A passive house was recognised as a low-energy house, which aims at "*significantly better* performance than required by Swedish Building Regulations BBR

16 (BFS 2008:20)" (Forum för energieffektiva byggnader, 2009a). A mini-energy house, like the low-energy house, was expected to have "*better* building performance than defined in Swedish Building regulations BBR 16 (BFS 2008:20)" (Forum för energieffektiva byggnader, 2009b).

The latest changes in Swedish Building Regulations (BBR2012) introduced a definition of low-energy and very low-energy buildings. Definitions included in BBR2012 describe low-energy buildings as buildings in which the space heating energy requirement[1] is lower than 75% of the requirements specified by current Building Regulations (9:8); space heating for very low-energy building should not exceed 50% of this requirement.

2.4.2. The passive house concept

The passive house concept as known today is the result of experience from many years of low-energy house construction. Among the many who have contributed to expanding knowledge and development of the passive house concept are: Professor Bo Adamson, architect Hans Eek, Robert Borsch Laaks, and Wolfgang Feist (Passive House Institute, Darmstadt, Germany; www.passive.de).

There are two definitions of "passive house" in Sweden: one international definition, promoted by the Passive House Institute in Darmstadt, Germany and a second, which has been formulated by the Forum for Energy-efficient Buildings (FEBY)(PHPP, 2007). The latter description of "passive house" is based on the same concept; however, adjustments to generally used standards in Sweden may slightly influence energy calculation results.

The Passive House Institute (PHI) defines a passive house as: *"a building for which thermal comfort (ISO 7730) can be achieved solely by post-heating or post-cooling of the fresh air mass, which is required to achieve sufficient indoor air quality conditions – without the need for additional recirculation of air."* (Passive House Institute, Darmstadt, Germany, www.passiv.de)

Wolfgang Feist, the founder of PHI, explains that fundamental to the passive house concept is thermal comfort, which is achieved by very good insulation of the airtight building envelope and by minimization of thermal bridges; hence overall heat losses are very small. Airtight building construction and good thermal insulation allow the building to retain warm air better during the winter season and leakage of cold outdoor air is minimized. Due to those attributes, the requirement for heating is significantly reduced and therefore the heating system may be simplified to complementary heating (e.g. heating with fresh air via an adequate ventilation system) or even be unnecessary. Even though the specific space heating (15 kWh/m^2) and/or heat load (10W/m^2) values for passive house must not be exceeded (Feist, et al., 2005), Feist explains that these measures are a consequence of concepts and energy-efficient design and not an aim in itself and that the difference in climate conditions calls for specific system solutions with regard to design, construction, ventilation and heating/cooling installation systems (Feist, First Step; What can be a Passive House in your region with your climate?, Passive House Institute, Darmstadt, Germany). Criteria for passive houses are briefly described in table 1.

[1] Space heating is understood as the sum of the energy distributed to the building and required for its general operation, heating, cooling and warm water.

Table 1. Passive house criteria PHI (Passive House Institute, PHPP 2007)

Space heating demand*	≤15kWh/m^2 (reference area) annually
Heat load*	≤10 W/ m^2 (reference area)
Primary energy (including domestic electricity, heating/cooling, building operation electricity)	≤120 kWh/ m^2 (reference area)annually
n_{50}-leakage rate (Pa50)	≤0,6 h^{-1}
Ventilation, with heat recovery efficiency	≥75%
*PHI certification requires that specific space heating or heating load values must be fulfilled	

In order to minimize heat and electricity demand, the Passive House standard requires that the annual demand of primary energy (sum of heating, hot water, auxiliary and household electricity) must not exceed 120 kWh/m^2a (per net floor area within the thermal envelope). By referring to primary energy, Passive House standard marks the importance of the energy source.

The airtight house requires a ventilation system which can also be used for heating. The supplied air is fresh and unpolluted; however, in order to achieve a very low heating energy demand, heat recovery from exhaust air must be utilized (Waltjen, et al., 2009). PHI recommends that ventilation aggregate units should have a minimum of 75% heat recovery efficiency. It is absolutely fundamental that a hygienic requirement (minimum fresh air volume of 30 m3/h per person) is fulfilled.

2.4.3. Swedish passive house standard

Even though development of the industrial construction of passive houses in Sweden is relatively slow, the first passive house that fulfils PHI standards was built as early as 2001. Designed by Hans Eek, 20 terrace houses in Göteborg (Lindås) became a milestone in low- energy building construction and showed that the Passive House concept can be successfully realised in the Scandinavian climate.

In 2007, *the Forum for energy efficient buildings (FEBY)* published the first Swedish passive house standard, which was replaced by new version in 2009, and later updated in 2012. According to a market report (Forum för energieffektiva byggnader, 2009c), 400 dwellings had been built to Swedish passive house standard in Sweden by March 2009, and it was calculated that in 2011 the Swedish passive house market would reach 3000 dwellings (Passivhuscentrum, http//www.passivehuscentrum.se).

It is specified that passive houses should achieve thermal comfort with minimum heating energy and maintain it by rational heat distribution of a hygienic air flow (Forum för Energieffektiva Byggnader, 2009a). Air heating is possible but not necessary as it is possible that heating can be delivered via a conventional heating system.

2.5. Zero-energy building

In the recast of the European Council Directive regarding Building Performance (2010/31/EU), yet another description of energy-efficient and environmentally conscious building was introduced:

(nearly) Zero Energy Buildings. A zero energy building might be generally described as a building that should be able to achieve a neutral life cycle, securing its low energy requirements from renewable energy sources. The literature shows that there are many different ways to specifically define what constitutes zero energy building (Hernandez and Kenny, 2010; Lund et al., 2011; Marszal and Heiselberg, 2011; Marszal et al., 2011; Sartori et al., 2012).

2.6. Conventional building (benchmark)

In order to be able to assess building performance, it is necessary to determine the benchmark, in other words, the standard that allows evaluation and objective interpretation of results. In the building industry, the construction standards can be used for benchmarking; hence, buildings which fulfil valid Swedish Building Regulations are considered here as the benchmark for new building construction and referred to as conventional buildings.

2.7. Overview of definitions

The aim of this chapter is to present different concepts related to environmental qualities of buildings and discuss the intentions behind those descriptions. Sustainable, green and energy-efficient buildings aim at adopting resource-efficient solutions, although these terms cannot always be safely used as synonyms. The sensible question is then how those different terms relate to each other.

Can energy-efficient building be “green”? Energy performance is only one of many assessment fields in environmental assessment methods (BREEAM, LEED or Green Star) and therefore if building environmental performance can be demonstrated in other assessment areas (e.g. material, water, waste) then the energy-efficient building can be named “green”. On the other hand, it is possible to reverse the question: is green building energy-efficient? A report prepared by the National Building Institute for the U.S. Green Building Council (Turner and Frankel, 2008) indicates that, on average, the energy performance of LEED buildings is better than the national average; however, in some cases, the predicted performance of the LEED buildings and the measured values differ significantly. Moreover, studies by Newsham et al. (2009) showed that there is “no statistically significant relationship between LEED certification level and energy use intensity”. Additionally, the report from BREEAM Consultation (2010) suggested shortcomings in energy efficiency assessment, indicating that BREEAM credits for energy efficiency in buildings should be strengthened and BREEAM certificated buildings performance monitored. A pitfall of building assessment tools might be the complexity of evaluation and the fact that the weight of individual parameters may only to some extent affect the final result. On the other hand, assessment methods allow the comprehensive environmental value of buildings to be highlighted.

It is possible to approach building evaluation using a three-dimensional framework: environmental, social and economic. Schnieders and Hermelink (2006) argued for sustainable value for passive houses, contending that “user-oriented design” and a focus on high quality in indoor environment contribute to the social component and that very low energy demand helps on the road to fulfilling environmental end economic conditions. Considering that the success of zero-energy building depends on successfully foreseeing future (energy) needs and securing them with renewable energy sources, this means that success in zero-energy building could fit into the definition of sustainable buildings. Figure 1 illustrates the relationship between different concepts related to environmental qualities of buildings.

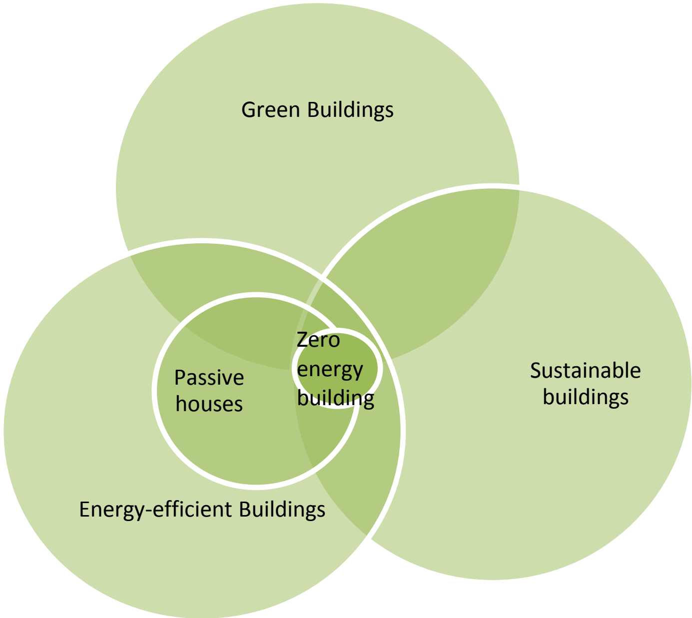

Figure 1. Overview of relationship between different concepts related to environmental qualities of buildings

Sustainable, green or energy-efficient buildings define concepts that ultimately aim at promoting better construction and responsible use of resources. However, it is the choices made in the course of design, production, management, operation and demolition which ultimatelly determine the resource-efficiency and total environmental impact of the building.

2.8. Practical definition used this thesis

Buildings designed and constructed with the goal of minimizing impact on the environment are expected to perform better than conventional buildings. In this study, buildings that fulfilled or nearly fulfilled passive house standard or/and buildings which were certified according to one of the environmental schemes for buildings were considered as buildings that have the potential to achieve sustainability goals. In this thesis, I refer to these buildings as *green*, *energy-efficient and low-energy* buildings. These terms are often used as synonyms, though I am aware of limitations within each term.

The benchmark, to which we can relate construction costs, building performance, perceived satisfaction and indoor quality, is a conventional building, designed and constructed according to current Swedish Building Regulations (BBR).

3. Method

3.1. The quasi-experimental approach

In this thesis, the assessment of energy-efficient green buildings has been generally made by comparison to conventional buildings, based on the premise that evaluation can only be achieved by referring to an acceptable base line, providing a benchmark for performance. One of the methods that builds on the concept of comparing similar groups is the quasi-experimental study. In this approach, objects are selected and grouped in such a way that all the relevant independent variables match except for the variable whose effect the researcher attempts to study (Nyström 2008). A quasi-experimental method has been applied in various studies from medical experiments and psychology to analysis of policies, industries and services (Bussing, 1999; Fagan and Iglesias, 1999; Reed and Rogers, 2003; Eliopoulos et al., 2004; Atterhög 2005).

The advantage of the quasi-experimental method is the possibility of controlling variables that may have a potential impact on measured variables. The buildings selected in this research were paired as closely as was possible, considering the location of buildings, their size, production year and potential customer segment. Firstly, I have searched for multi-family buildings that fulfill the research definition of green building. After selecting the green buildings, I have looked for controlled objects, conventional buildings that fulfill in the best manner the above-mentioned objectives. During the course of this research, a total of ten energy-efficient green and ten conventional multi-family buildings have been carefully selected.

The quasi-experimental approach was used to investigate whether there is a difference between the opinions of occupants living in green and conventional building occupants focusing on investigating occupants' overall satisfaction, perceived quality of indoor environment and potential problems appearing in the building. The results were described in papers II and IV. In papers V and VI, the same method was applied; however, the focal points were the importance of environmental factors from a customer perspective and occupants' willingness to pay for green buildings, respectively.

The papers are included in the thesis chronologically, i.e. according to the time when the papers were written, rather that ordered according to method used or (developer or customer) perspective investigated. Figure 2 presents design and methods applied in the thesis.

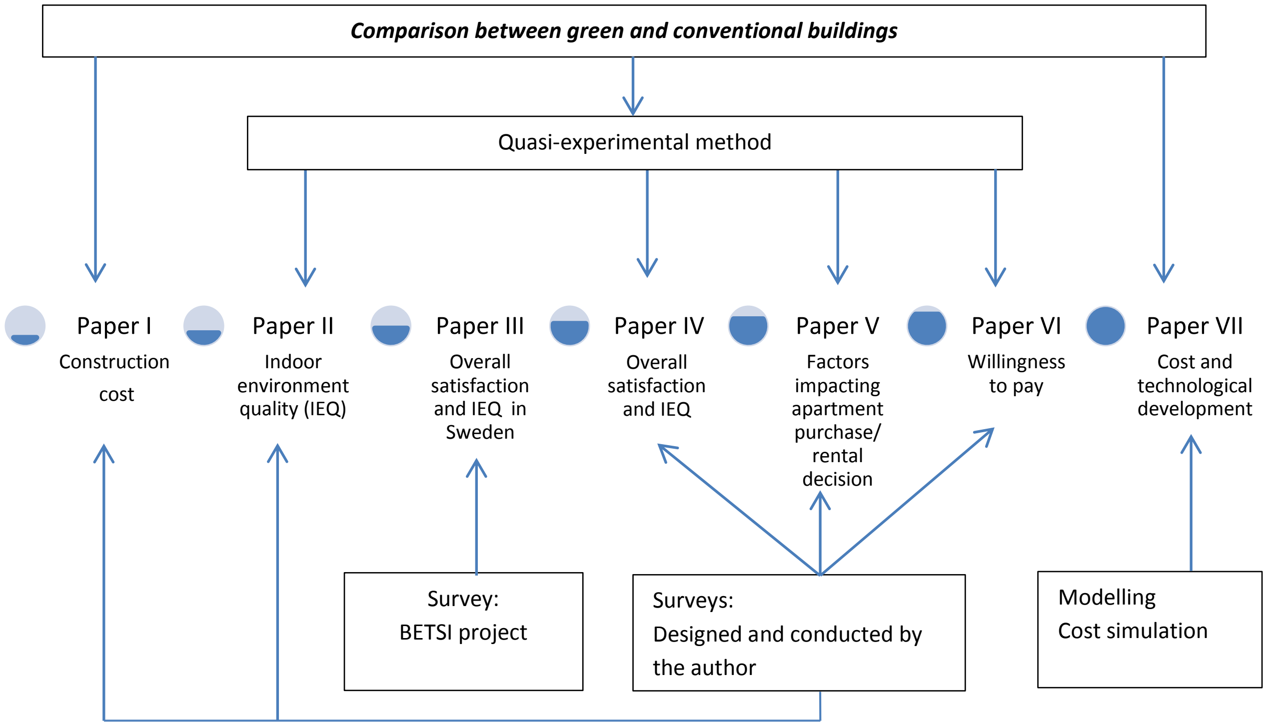

Figure 2. Design and methods applied in the thesis.

3.2. Limitations

Unfortunately, in reality we are unable to control all the factors and we must accept nearly-perfect solutions. Each property is unique in form, design and exposure to local climate conditions. These elements may have an effect on building performance, but also on occupants' opinion. Secondly, certain limitations come from the approach itself. The buildings were specifically chosen due to their characteristics and not randomly selected. Even though the buildings described in this thesis represent the majority of multi-family energy-efficient buildings constructed in Sweden, they may not be representative of the total population.

In this thesis, both a quantitative and a qualitative approach were applied. The number of observations (papers II,III,IV, V and VI) allows for a quantitative approach in data analysis; on the other hand, the approach employed in data collection (quasi-experimental study, survey questionnaire, interviews) is often used in qualitative research and therefore subject to criticism for being subjective, difficult to replicate and posing problems of generalization (Bryman, 2012).

Since I was unable to triangulate data collected via the survey with real construction costs (paper I) or prices (paper VI) or in-use measurements such as energy consumption (papers II,III and IV), the present study is largely based on experience and the personal opinion of respondents. Consequently, the analysis may include errors related to the formulation of the questions, respondents' subjective opinion and their selective memory (Schwarz and Oyserman, 2001).

Finally, challenges may emerge while constructing, estimating and interpreting regression models when the data set has a paired structure, as in the case of data based on observation of twins. Carlin et al. (2005) suggested that the pairing characteristics of data should be taken into consideration when fitting it to a regression model. The authors indicated that the assumption of a difference between outcome values for a given difference between covariate values being equal when comparing two unrelated individuals and two twins may be untrue. After discussion, the authors suggest that more adequate results are computed if the general model includes a coefficient for pair effect.

Since certain characteristics of green building are not as directly explanatory of conventional building characteristics as is the case in twin studies, it is possible that concerns regarding statistical models indicated in Carlin et al. (2005) may not apply in our case. However, considering limitations of research design, data collection and analysis, the results should be interpreted with caution.

3.3. Theory and tested hypothesis

It is my conscious choice not to include a theory chapter in this part of the thesis. The reason is that the scientific theories which underpin this research are eclectic: selected and used as was considered most relevant in regard to the objective and framework of the particular study. Consequently, the theoretical background and the literature review are presented in the respective papers included in the thesis.

The reader might also be surprised by how rarely I have used the word "hypothesis" in the thesis. This, however, does not mean that no hypotheses are put forward or tested. The propositions are indeed stated silently and the results of various statistical tests aim to help find the answer to and explain the studied phenomena as indicated in the objectives.

4. Summary of the papers

The results of this research are presented in seven papers (the structure is presented in figure 3). *Paper I* focused on the developers' perspective and investigated the cost and investment viability of green and conventional buildings. *Papers II-VI* focused on the occupants' perspective, investigating how the perceived indoor environment affects occupants' satisfaction. *Papers II and IV* aimed at comparing responses from occupants living in green and conventional residential buildings and focused on differences in occupants' satisfaction, operation and management between those two types of buildings. *Paper III* presents a more general picture of residential buildings in Sweden by analysing overall satisfaction and the perceived indoor environment quality on a national level. *Paper III* uses data from a survey commissioned by the Swedish National Board of Housing, Building and Planning (*Boverket*), with results being representative of all adults living in multi-family apartments in Sweden. *Papers V* and *VI* aimed at investigating the importance of environmental factors in customers' purchasing decisions and analysing stated willingness to pay for green buildings, respectively. Results presented in the latter paper are also interesting from a developers' perspective, as willingness to pay represents potential income for the developer. Finally, *paper VII* looked at profit and construction costs of energy-efficient buildings considering gains and losses of saleable floor area. This paper explored the effect that new energy-efficient products may have on the profitability of energy-efficient building construction.

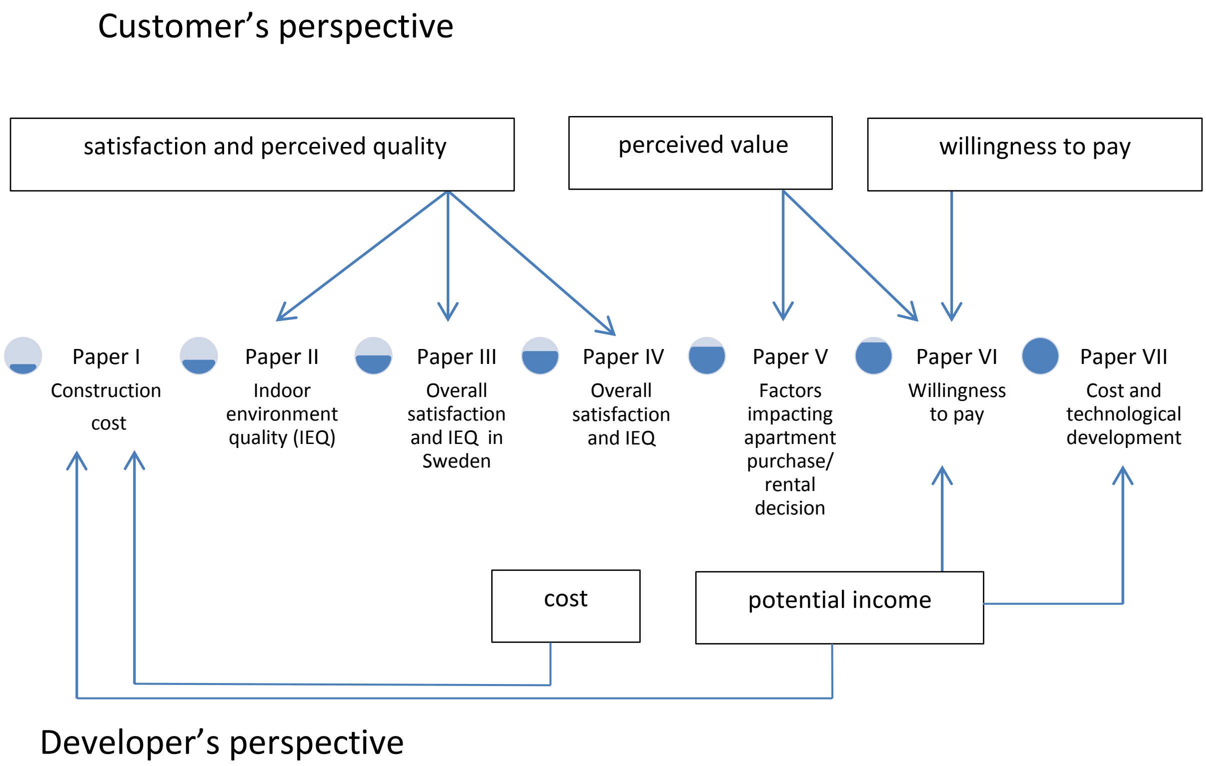

Figure 3. Structure of the thesis.

Paper I

Zalejska-Jonsson A., Lind H. and Hintze S., (2012) "Low-energy versus conventional residential buildings: cost and profit." ***Journal of European Real Estate Research,*** **vol. 5 issue 3, pp: 211-228**

The aim of this paper was to investigate the cost and investment potential of low-energy and conventional residential buildings, considering reduction in operating cost. The profitability of investment in "green" and conventional residential building was evaluated using an equity investment model: net present value. The assessment of the difference in construction cost was based on responses received from a survey addressed to chief executives and project managers of construction companies that had experience of construction of low-energy multi-family buildings in Sweden. The estimate for operating cost was based on the difference in energy requirement between low-energy and conventional buildings and on responses received from a survey and interviews conducted with housing managers.

The responses received from private and public construction companies implied that labour and material cost varied most between "green" and conventional construction. Interestingly, respondents stated that the labour cost decreased with increasing experience of low-energy construction and the development of construction technologies may constitute the greatest contribution to the development of low-energy building construction.

The results indicate that at 5 per cent higher construction costs for low-energy buildings and at the assumed energy prices, considering a holding period of 20 years, the energy savings are sufficient to defray the extra investment cost.

Paper II

Zalejska-Jonsson A. (2012), "Evaluation of low-energy and conventional residential buildings from occupants' perspective." ***Building and Environment*** **Vol. 58, pp: 135-144**

The paper aimed at assessing building performance through investigating occupants' satisfaction with indoor environment in residential buildings. The paper focused on differences that may occur between operation, management and satisfaction of tenants living in low-energy and conventional buildings. The study was limited to multi-family buildings with rental apartments. Survey responses received from 256 tenants living in low-energy and conventional multi-family buildings were used to create a data set.

The results indicated that satisfied and dissatisfied tenants live in both low-energy and conventional buildings. Tenants living in low-energy buildings showed high satisfaction with air quality and sound insulation in their dwellings, but were more prone to experience colder temperatures and chose to use supplementary heating. However, concerns about heating and ventilation were reported in both types of buildings.

Interestingly, occupants living in green buildings indicated that they were proud to live in an environmentally conscious building. Occupants indicated that their environmental awareness increased and affected their behaviour.

Feedback received from housing managers indicated that there is relatively little difference in operating low-energy and conventional buildings; however, adjustment of HVCA insulation and heating could be challenging. It seemed that housing managers and occupants experienced problems particularly with the efficiency and effective operation of the HVAC system.

Paper III

Zalejska-Jonsson A. and Wilhelmsson M. (2013) "Impact of perceived indoor environment quality on overall satisfaction in Swedish dwellings." ***Building and Environment*** **Vol. 63, pp. 134-144**

The ambition of this paper was to investigate the impact that aspects of indoor environment quality may have on occupants' satisfaction. The analysis is based on survey responses collected during the project *BETSI* commissioned by *Boverket* (The Swedish National Board of Housing, Building and Planning). The results are representative for all adults living in multi-family apartments in Sweden.

The results indicate that perception of indoor air quality has the greatest effect on occupants' overall satisfaction. It was found that experiencing problems with draught, dust and too low temperature negatively affects overall satisfaction.

Occupants' satisfaction may also be affected by both building and individual characteristics. It was found that the relative importance of factors impacting overall satisfaction may differ depending on location, building construction year, occupant gender and lifestyle.

Paper IV

Zalejska-Jonsson A. "Parameters contributing to occupants' satisfaction: Occupants' insights into green and conventional residential buildings"; paper accepted for publication in ***Facilities***

The goal of this paper was to study the impact of perceived indoor environment quality on occupants' satisfaction, and by investigating buildings with both rental and owned apartments, we aimed to explore whether apartment tenure may have an effect on the difference between green and conventional buildings.

The findings showed that occupants are very satisfied with their apartments. The analysis indicated no statistically significant difference in the opinion of occupants living in green and conventional buildings; however, a statistically significant difference was found between occupants living in rental and owned apartments.

The lowest satisfaction scores were given to thermal comfort. Findings imply that satisfaction with thermal comfort varies between occupants depending on the time of year. Generally, occupants in green buildings found indoor temperature too low in the winter, but more satisfactory in the summer than those living in conventional buildings. The opinion of owners of green and conventional dwellings differed at a statistical level. Occupants living in green apartments indicated they were more pleased with sound quality than those living in conventional dwellings. With regard to acceptance of air and light quality, the difference in occupants' opinion was significant depending on apartment tenure, but not on the environmental profile of the buildings. It was found that perception of thermal quality and of air quality have a significant effect on occupants' overall satisfaction.

The findings also indicated that building performance and occupants' satisfaction can be affected by the owner's ability to ensure that the HVAC system works effectively. The findings indicate that buildings with owned apartments are more vulnerable to this kind of problem, often because of the owner's limited technical competence, failure or lack of communication with installation or construction companies. In the case of buildings with rental apartments, the responsibility of housing managers is to secure effective system operation.

Paper V

Zalejska-Jonsson A. (2013) "Impact of energy and environmental factors in the decision to purchase or rent an apartment: The case of Sweden" Paper accepted for publication in *Journal of Sustainable Real Estate* vol. 5

The focus of this paper is on examining how the impact of energy and environmental building features are being factored into decisions to rent or buy apartments. The paper demonstrates that energy and environmental building performance environmental factors have rather a minor impact on the purchasing or renting decision. Our findings indicate that when discussing the impact of energy and environmental factors on a customer purchase decision, information availability should be considered. Moreover, the results suggest that availability of information on building environmental features increases the likelihood of the buyers' interest in this information.

Paper VI

Zalejska-Jonsson A. (2013) " Stated WTP and rational WTP: willingness to pay for green apartments in Sweden" Submitted to *Sustainable Cities and Society*

Considering that green buildings are expected to require lower operating costs, provide better indoor environment and have a lower impact on the environment than conventional buildings, it is rational to believe that a customer is willing to pay extra if perceived benefits from renting or buying green property are more beneficial than those from conventional buildings.

The aim of this paper was to study stated and rational willingness to pay for green apartments in Sweden. A database of responses from occupants living in green and conventional multi-family buildings was used to investigate the existence of WTP and to test differences in opinion between respondents living in green or conventional buildings and condominiums or rental apartments.

The responses indicate that people are prepared to pay more for very low-energy buildings but not as willing to pay for a building with an environmental certificate. It was found that interest in and the perceived importance of energy and environmental factors affect the stated WTP. The results indicate that a stated willingness to pay for low-energy buildings of 5% can be considered a rational investment decision.

Paper VII

Zalejska-Jonsson, Agnieszka; Lind, Hans; Hintze, Staffan. 2013. "Energy-Efficient Technologies and the Building's Saleable Floor Area: Bust or Boost for Highly-Efficient Green Construction?" Buildings 3, no. 3: 570-587.

The paper explored floor area losses that developers encounter when constructing energy-efficient buildings and investigated the possible effect of new technologies on construction cost and floor area balance.

The results show that the profitability of constructing energy-efficient buildings can be significantly reduced due to floor area losses. The paper shows that construction of energy-efficient buildings and introducing very energy-efficient technologies may be energy- and cost-effective even when compared with conventional buildings. This result indicates that policies aiming at high energy-efficient construction should actively promote and support the implementation of the newest technologies.

5. Results and contribution

The ambition of this thesis was to investigate the comprehensive value and assess the investment potential of green residential buildings. The research showed that building highly energy-efficient green buildings can be an attractive investment from both the developer and the customer perspective. New technologies and experience can contribute significantly to decreasing construction costs and consequently improve profitability. Moreover, the improved transparency and comparability of information may influence customers' interest in energy and environmental factors. Environmental education is also a significant factor, particularly in assessing the price that the customer is willing to pay.

The research results imply that constructing green residential buildings is a rational strategy for a developer. However, there is a probable risk that a company may see the potential in green strategy, but yet not be willing to deliver the product. Kirchhoff showed (2000) that the strategy of overcompensating is rational if there is a very low risk of a company being exposed if it fails to apply to the green standards. Unfortunately, this issue may apply to the building industry. Building regulations really require developers to present evidence of complying with the building standards, and research has shown (e.g. Bordass et al., 2001; Leaman and Bordass, 2001) that the gap between designed and constructed buildings is significant.

In the case of building construction in Sweden, the latest Swedish Building Regulations (BBR2012) indicate that developers should verify through calculation and measurement those buildings whose energy requirements are fulfilled (9:2). It is suggested that the validation of energy requirements should be carried out over a 12-month period and results should be disclosed two years after occupancy of the building. Disclosure of energy consumption values, which may be adjusted by taking into account outdoor temperature and users' behaviour, may not be sufficient to secure good quality low-energy building construction. The message of this thesis is that building energy consumption values may not tell the whole story. Developer responsibility needs to extend to the post-occupation phase. It is imperative that developers not only design, build and sell highly energy-efficient green buildings, but also ensure that the building is energy-efficient during the operation phase. This thesis shows that post-occupancy assessment, feedback from occupants and improved commissioning strategies are the methods that developers should consider. Failing to validate energy-efficiency and quality of indoor environment calls into question the value of the product delivered to the customer.

Finally, the results presented in the thesis indicate the customers' high level of overall satisfaction with purchased or rental apartments. On the other hand, the delivered quality indicated by level of acceptance of indoor environment was satisfactory, but showed a potential for improvement. Particularly, greater value can be delivered in the case of perceived thermal quality. Considering that perceived quality of indoor environment has an effect on occupants' satisfaction and that occupants' behaviour may have an effect on building performance, it is very important to further examine and attend to these issues.

This thesis makes a humble contribution to better understanding occupants' needs and expectations; it contributes to knowledge of low-energy residential buildings and takes a small step towards understanding factors that affect green building development.

6. Future studies

The results presented in this thesis indicated a few issues that need further attention and investigation. First, future study should focus on how responsibility for securing efficient building operation can be applied in a business model. The gap between building construction and operation has been discussed for many years now; however, the need to find the most appropriate solution has never been more urgent.

Secondly, global warming requires change that is the responsibility of all of us, as a group and as individuals. Future research could explore further how communication can improve environmental awareness, education and affect customers' behaviour and the decision-making process.

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