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Salvageability of building materials

Reasons, criteria and consequences regarding architectural design that facilitate reuse and recycling

Thesis for the degree of Philosophiae Doctor

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Summary

This thesis focuses on resource efficiency of building materials achieved through facilitating reuse and recycling of components. The overriding scope is to investigate building methods that may contribute to solving a set of environmental challenges in a long-term perspective, and to explore ways to expand the applicability and transfer the concept to contemporary architectural practice. The aim of the work is to contribute to new understanding in this field, both at the level of design, and at a more general level of the building trade where the drivers and the hurdles for environmental considerations are complex and interconnected. The thesis uses a multi-disciplinary approach and the investigations are carried out with a diversity of methods including quantitative and qualitative assessments, literature studies, case studies and discussions. The findings and reflections are seen as puzzle pieces that try to make the picture of life cycle design more complete.

The main work in the thesis is divided in three sections that make contributions to separate areas of inquiry, headed under the questions "WHY", "HOW" and "SO WHAT". These consist in total of five papers that build upon each other and that are written and presented in a chronological order.

The quantitative analysis in the paper discussing the question "WHY" aims at substantiating the environmental rationale for facilitating reuse and recycling. An introduction of the concept *environmentally justifiable lifetime* initiates an exploration of the normative relationship between environmental impact and the number of functional lifetimes of components. A quantification of greenhouse gas-emissions related to extraction, production and transport of building materials is set as a point of departure for a calculation of expected lifetime, or "pay-back time" for ten exterior wall constructions. The comparative results reveal large differences in impact between the construction materials and subsequently large differences in the need for salvageability. The conclusion is that assessed environmental costs can complement forecasted turnover as a rationale for salvageable design. The calculation method that was used represents a quantifiable measure for expected building generations. This contribution may help enlarging the scope for salvageability.

The overriding question in "HOW" is how building design can facilitate future deconstruction and salvage of materials. First, existing research on *Design for Disassembly* (DfD) is analyzed, and a principal systematization of design guidelines is presented. The guidelines are divided into *scale* of application, main *criteria* and prescriptive *strategies,* and are structured in a matrix that may also be used as a tool for assessment. The aim is to create a consistent and multi-purpose base of information to be used in the rest of the work. Furthermore, as the term

Design for Disassembly only reflects the disassembly phase, the term *salvageability* is suggested as a more adequate replacement.

Then two case-studies are performed. The first case-study assesses the reusability of massive wood component types and the second investigates brickwork constructions. The assessment matrix is used in both studies. Also, the background and the practical, technical and architectural consequences of the design measures for each criterion are explained and discussed. Both case-studies show that the examples of historical construction methods hold an overall high reusability, not only due to high scores for *reversible connections* but for all the criteria regarding salvageability. Furthermore, both studies show that there are great potentials to improve the reusability for the most commonly used constructions in massive wood and brickwork today. The assessment method itself is also commented upon.

The aim of "SO WHAT" is to discuss the architectural consequences of the design strategies. The overriding hypothesis is that the demand for salvageability of building materials may be seen as a positive driver for architectural design. As in the case-studies, the framework of the study is based upon the criteria for salvageability. The research investigates in what ways this field of knowledge may influence building practice and architectural expression, and points to building examples from past and present. The discussions verify the hypothesis, and show that some of the criteria may have great consequences for building design. The study furthermore explores the concept of tectonics and in what ways environmental logic can substantiate architectural articulation. The focus shifts from the restrictions that the demand for salvageability may pose upon construction, and rather point to the potential for creating meaningful architecture in a low-carbon society.

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intro-duction

1.0

1.1 Preface

TWO STORIES

Trondheim 1841- 44

After two large fires in 1841 and 1842, some 745 wooden buildings were destroyed; homes, stores, workshops and warehouses. This corresponded to more than half of the total building mass in Trondheim at that time, and the events must be regarded as catastrophical for the city. However, it took less than two years to rebuild. The surrounding countryside was used for material sourcing: Timber houses were disassembled and moved, preferably rafted, from the districts and re-erected in town. Some of these buildings were earlier used and now accidentally vacant, whereas others were newly made by farmers with logging as a subsidiary income. Evidenced in newspaper ads where these objects were offered for sale, as much as one third of the houses constituting the new building mass of Trondheim could have come from the city's surroundings (Larsen 1989).

The remarkable speed of the construction was greatly conditioned by the simple building method of the log house. The vernacular house design facilitates easy disassembly and reuse of logs as well as relocation of whole buildings. Craftsmen in town and country had common skills and knowledge about this traditional way of building, and the wood material that was used for just about every detail of the houses was locally produced (Personal communication with the Director of Cultural Heritage Management Gunnar Houen, 2008).

Disregarding the high speed of construction, the houses still obtained a durable quality demonstrated in materials and craftsmanship, and many of them are still in use in the centre of Trondheim today, 165 years later.

Trondheim 2008

While writing the introductory parts of this thesis, two office-buildings in Søndregate are being demolished to give way for new headquarters for a Norwegian bank. Although the buildings were only 32 years old, they proved difficult to adapt to new requirements for energy performance and flexibility (SMN 2008). The buildings can be regarded as contemporary "state of the art" construction, and consist of a great variety of materials.

Current regulations for Norwegian demolition activity, enforced from 2008, require a *waste plan* to document the volumes and the directional flows of the building waste, and a minimum source separation of 60 % (weight percentage). In Søndregate, more than 90 % of the waste will be recycled. The dominant fraction is concrete, and the reinforcement is disintegrated from the slabs by large jacks with "concrete scissors". The steel is then shipped for remolding at the iron works in Mo i Rana, and the crushed concrete is used as hardcore in a local building project. The wood fraction is shredded and used for energy recovery, and the large glass façades will be used in the production of mineral wool at Stjørdal. Extra caution is paid to the dismantling of the asbestos cement sheeting of the exterior walls. Also, some of the windows had casings containing PCB and had to be treated as toxic waste. The final residual waste thus consists of insulation materials, floorings, plastics and mixed debris (Project waste plan, on-site survey and personal communication with Paal Arne Sellæg at demolition contractor AF Decom, and with Øyvind Spjøtvold at NORSAS consultants 2008).

Ideas for recycling on the site have been discussed. However, these efforts are generally considered to represent a cost hurdle by delaying the demolition process. Furthermore, various possibilities for reuse of components in the new buildings were rejected by the contractor because of the uncertainty involved. A surviving option for material salvage might be the slate roof which is planned to be remounted in an interior setting (Personal communication with Sevrin Gjerde and Svend Johnny Breiby at Agraff architects and with project manager Trygve Leiksett at Sparebank 1 Midt-Norge 2008).

REFLECTIONS

Based on these two stories, one could point to some significant changes in the building trade that occurred within this time span. Without performing any advanced lifecycle analysis, it is possible to make some assumptions about the impacts of the general material use involved. It is also possible to elaborate on the development of the ways buildings are built regarding the complexity of construction techniques. Moreover, the vulnerability and emergency management related to a society's building mass could be an interesting topic to address.

A striking issue is the massive transition from reuse to recycling. Today, in an industrial context, only recycling is a financially viable option. However, as recycling involves additional impacts associated with transport, auxiliary materials and energy use for the processing, it may not always be environmentally recommendable (Roth 2006). From an architect's point of view, salvage of whole components represents a more "intelligent" level compared to the recycling option because the implementation involves careful consideration and special detailing that may also have architectural significance. Building systems that facilitate reuse is common in vernacular traditions, but in current architecture it is usually reserved for projects with short lifetime expectancies such as exhibition pavilions. Thus, in general, contemporary buildings are not designed for reuse.

Facing climate change, it is timely to consider the fundamental ways of producing buildings. Meteorologists have showed that developments of the global climate has great inertia, and that the cuts that we eventually are able to make in greenhouse gas-emissions now will not have any effect for at least 20 years.

Inertia is also characterizing our building mass, which can be regarded a social-ecological system representing important real capital as well as multiple-related flows (Moffatt and Kohler 2008). Changes in material use and construction techniques may instantly affect the primary resource use, but will not have impact on the waste handling in the deconstruction phase for decades. This time-lag implies that coming generations have to deal with the consequences of our choices. In the same way as the graveness of future climate change is an effect of today's consumption and lifestyle patterns, future waste handling and potential for material supply through reuse, will be determined by the current choices we make in architectural design.

SCOPE OF THESIS

The focus is on design for reuse of building components with the overall aim kept on resource efficiency. The term "salvageability" is introduced to describe the desired characteristics of the design concepts based on these ideas. In discussing the recommended measures, a primary objective has been to investigate building methods that may contribute to solving a set of environmental challenges in a long-term perspective. Here, vernacular building methods have been an important source of reference. A secondary objective of the work has been to operationalize these design concepts and bring them closer to contemporary architectural practice. Although there seems to be a significant base of knowledge about how to design for salvageability, this knowledge is still mainly pursued as an academic exercise far from common building tasks. Thus, the overriding scope of this thesis is twofold:

- To investigate building methods that facilitate reuse and at the same time contribute to solving a set of environmental challenges in a long-term perspective
- To explore ways to expand the applicability for salvageability and to transfer the concept to contemporary architectural practice

When discussing salvageability, there are many considerations that must be seen in relation to each other. I therefore see this field as a broad research area. I believe that the challenges it raises cannot be solved by following only one line of action, and I have therefore chosen to investigate different aspects. The addressed problems convey a search for new insight, and the investigations are explorative in nature. Salvageability is looked at from different angles, and the research is divided in three sections. The environmental reasons are discussed in "WHY", the design criteria are discussed in "HOW" and the architectural consequences are discussed in "SO WHAT". Depending on the nature of the inquiries, different methods are applied. The research questions and the accompanying methodologies are further explained in sub-chapter 1.5.

The use of the term *salvageability* has been chosen after a search for an English equivalent of the Norwegian *gjenbrukbarhet*. To salvage means to save or rescue, and in the context of building materials it may comprise both reuse and recycling. *Salvation* is defined as: "the act of saving or protecting from harm, risk, loss, destruction, etc." (http://dictionary.reference.com 2009) The term thus points futher than to pure economic and technical benefits. With the risk of misinterpreting the English language, to me salvageability also seems to reflect *caretaking*. It may thus engage other faculties of the mind than the pure self-interest and tie to maintenance and preservation. Taking care of buildings can be seen as an aspect of taking care of the environment. As further described and argued in 3.1 "Salvageability of building materials", it is suggested as a replacement for the term "Design for Disassembly". This being said, the term *salvageability* is unusual and to my knowledge it has not been used in this context before. In the end, other readers will have to judge whether or not it is a good suggestion.

1.2 Background

THE ENVIRONMENTAL CHALLENGE

As there is a rich selection of literature in which this issue is elaborated in detail, the environmental crisis, characterized by rapid and often irreversible ecological changes on Earth caused by human activities, is taken as a given fact and not extensively discussed here. As an indicator of the public awareness, climate change is now frequently considered in all media and in the political debate, and the dominant international leadership has - during the five years in which this thesis has taken shape - reached consensus that global action must be taken. Important to remember, however; the environmental challenge also regards other important topics such as loss of habitats and species, resource depletion and the spread of toxic and persistent chemicals. All these indicators show that the carrying capasities of the natural environment are heavily violated, and that changes in the consumption patterns, particularly in the rich parts of the world, are urgent.

The environmental challenge is seen as a principal problem, and is used as an embedded framework for drawing up the background as well as the research questions of this thesis.

SUSTAINABLE BUILDING

Sustainable building is a response in the building sector to the environmental challenge. Research related to sustainable building involves a range of issues mainly centred on energy use and material selection. The starting points have been several: A need to cut the national energy consumption, wishes to reduce heating costs, depletion of raw material resources and negative health effects from building emissions. Focus and vocabulary may shift from project to project, over time and in between architects. However, the terms sustainability and sustainable development, integrating environmental, economic and social considerations, imply broad approaches.

The energy consumption in the user phase of a building may run up to around 90% of the total energy use in the lifecycle of a conventional building (Fossdal 1995). As a response to this, a main share of the research so far carried out is targeted to reduce this impact. However, this relative figure is changing with the ever-increasing thermal insulation requirements on the building envelope. More materials are needed in a high-performance exterior skin, at the same time as the energy use for the buildings' operation phase decreases. In this way, the relative impact between energy use for material production and building operation changes. This gives way to more focus on the embodied energy in the materials, and subsequently on their potentials of reuse and recycling (Thormark 2001). These potentials, or the *salvageability,* are however not yet thoroughly discussed, and far less incorporated, as an issue for the contemporary building trade.

Also, when not only energy use, but also other environmental indicators like CO_2-equivalents, pollution, waste, health and biodiversity are investigated; we see that materials are responsible for major loads. This will, in turn, lead to more focus on the production processes (Berge 2000, Fossdal 1995, Kibert 2007). In the Norwegian context, where electricity generated by hydropower is mainly used for heating purposes whereas carbon fuels are common in the production of materials, this relation becomes particularly relevant. A recent study shows that the carbon emissions resulting from extraction, production and transport of building materials in Norway is about twice compared to the figure for the emissions resulting from building operation (Bernhard et al. 2006). The accounting for hydropower as a carbon-neutral energy source is controversial, and this discussion will not be pursued here. However, it can be pointed out that a focus on the environmental effects of building materials probably will increase as the complexity of these investigations is expanded.

An additional rationale for investigating environmental impacts of the material use is that buildings' turnover is increasing. Due to rapid changes in society, business life and family structures we experience faster changing functional demands on our buildings, and the buildings' actual service lives are reduced. The real estate business also contributes in speeding up the market fluctuations so that sustained continuity in the building mass is recurringly interrupted. As an extreme example; average lifetime for a high-rise office building in Tokyo in the 1980s was as low as 17 years (Brand 1994 p. 82). Also in Scandinavia, and even within the housing sector, turnover is increasing: During the last 7-8 years, about 25% of all demolished apartments in Sweden were younger than 30 years old, whereas ten-fifteen years ago this was unheard of (Statistics Sweden, personal communication with Catarina Thormark 2005). Building structures are demolished and sent to landfill independent of their technical quality because a potential second hand use is not financially profitable. This relation can be expressed as a mismatch between the technical lifetime of components and the service life of a the buildings they are parts of. This mismatch is seen as a major problem in this thesis because it has negative environmental consequences in both ends of the material flow through the building industry. Increased turnover increases the upstream pressure on new raw materials as well as on the downstream waste handling with growing landfills and toxic emissions..

The environmental impacts associated with building materials are complex and can be remote with regard to both location and time. The effects of a devastating exploitation of natural resources may not be charged to the users of the finished building as the construction may take place in a different part of the world, and the effects of hazardous emissions on human health may not be apparent before decades later (Sassi 2006a). Compared to the relatively simple methods of calculating energy demand for building operation; assessments of building materials include impacts generated in the products' lifecycle of extraction, production, transport, maintenance and demolition. Different challenges and opportunities are connected to different materials, and a range of indicators may be decisive for the final environmental profile (Berge 2000).

The connection between the environmental impacts of building materials and the salvageability can be viewed from different angles. Several studies are based upon an assumption that there is generally a positive environmental effect of designing for disassembly because facilitating for reuse and recycling can save new resources independent of the specific material in question (Crowther 2003, Durmisevic 2006). Some studies argue that high impact materials also have correspondingly high potentials for environmental savings through reuse or recycling. Thormark (2001) uses the concept of *recycling potential* as a way to express how much of all embodied energy used in a building that could, through recycling, be made usable after demolition, and case studies are performed to demonstrate this relation. Other literature point out that biodegradable materials belong to a natural closed loop cycle, and therefore not only typically have low environmental impact for production but also require fewer reprocessing resources and represent less pollution after their initial service lives (Berge 2005, Sassi 2006b). Thus, different material groups are not only suitable for different practical end of life options such as reuse, reprocessing, heat recovery or biodegrading, but they have also various environmental rationales concerning salvageability.

The rationale for salvageability can furthermore be connected to the components' service life and turnover frequency. As this regards type of building as well as building part, studies have investigated which building types and building parts that are mostly exposed to remodeling, replacements or demolition (Fletcher 2001, Sassi 2000). When linking turnover frequency with environmental impact of the materials, a remaining question is whether or not components and materials with high environmental loads should also be prepared for second service lives, and if so; which materials are mostly in need of salvageability?

LEARNING FROM HISTORY

Vernacular buildings from all over the world are often pointed to as good examples of environmental architecture: Space efficiency, bioclimatic design and use of local and renewable materials are typical traits. In addition to this, many cultures have developed building systems that are dismountable, and thereby facilitate ease of reparations and replacements of damaged or worn out materials (Crowther 2003). Also, after the buildings' service life, it is easy to separate the materials during deconstruction, which increases the reuse potential (Myhre 1996). The traditional Norwegian log house and brickwork laid with lime mortar are examples of dismountable constructions.

However, we have not been able to bring these design principles into the modern building industry. Changes in the manufacturing conditions have been considerable the last century. We have moved from utilizing a few, well known building materials to several 100.000s, composed of differently processed materials and a range of additives. Furthermore, often building components of different materials and qualities are permanently fixed to each other and service systems baked into the constructions. Even though source separation at construction and demolition sites now has become common practice, it is obvious that taking care of such an amount of assorted material fractions in an environmentally optimized way is quite a challenge. The manufacturing industry has at the same time become more centralized, and distance between production and building site may be long. Transport is often a determining factor both in the assessment of environmental effect, and as an economical and practical hindrance for efficient recycling (Bohne 2005).

We do have some, also Norwegian examples of ”recycled buildings”, meaning buildings made of materials from deconstructed houses. Some of them are innovative and architecturally interesting, and reused components may be highlighted and viewed as additional qualities. Also recycling of scrap iron and crushing of concrete to hardcore for road construction has long been in practice, showing economical gain. However, the post-war building stock is not planned to be taken apart for reuse or recycling, whereas most older buildings actually were. It appears as a paradox when bricks carefully salvaged from buildings of the 1800s are reused in new walls and laid with cement mortar. The very reason it is feasible to deconstruct the old brick walls is the flexible lime mortar commonly used at that time. With the solid cement mortar, no more future lifetimes can be obtained.

In a culture of salvageable construction, buildings may be viewed as “material banks” for the future. If we could reintroduce future deconstruction and reuse as premises for new design, environmental advantages could be gained through reduced raw material and energy needs, as well as through reduced emissions and waste. Since traditional building methods often facilitate salvage, it would be interesting to investigate the specific differences between traditional and contemporary buildings. Studies that compare building methods in a chronological order could help document what have happened on the way in the transformation of building constructions as well as point to favourable alternatives for further developments.

LEARNING FROM ECO-DESIGN

Within the field of Product Design, the issue of material use in a lifecycle perspective has been vigorously investigated during the past two decades. The strategies of *eco-design* have also been implemented in production; systems for product retrieval and recycling have become mandatory for producers of electric and electronic (EE-) articles within the EEA area, and are also under implementation for automobile manufacturers. Eco-design explains how to improve environmental performance throughout the life cycle of a product, and *dematerialisation* - to create more with less - and planning for future reuse are two important steps (Wigum 2004).

Ideally, the design process should start with analyzing people's real needs, and assess if these needs can be fulfilled in alternative ways. Design can eventually be carried out immaterially when designing services instead of products. If we were able to shift our prevalent attitude from viewing products as endpoints in themselves to seeing them as providing functions to the users, we could reduce resource use and waste streams. Using the car as an example; according to this view one would not purchase a vehicle, but rather the function of transport. As a result the manufacturer would keep prime ownership and also be responsible for the end of life treatment.

As conventional buildings usually have longer life spans than most consumer products, planning for future reuse has not been an extensively pursued issue within the contemporary building industry. Also, as buildings cannot be subjected to mass production in the same way, the financial motive for future reuse and recycling is less apparent. Thus, constructions today are usually designed in such a way that demolition and incineration, possibly crushing into fill material is the only viable alternative when the components have served their function.

However, the lifecycle perspective of materials has also been investigated by architects. When Buckminster Fuller designed the "Dymaxion House" project in 1941, he proposed that the house-owners would not own the materials of the building, but simply rent them from the manufacturer - who then would be responsible for service, repair and new model replacement. The building would eventually be disassembled for material recycling (Crowther 2003). Fuller was introducing the now more recognised notions of product stewardship and extended producer responsibility, which give strong incentives for design for extended useful life and maximum recoverable value after use. Today, as buildings' turnover increase, the eco-design approaches to industrial production of building components seem more and more relevant.

LEARNING FROM INDUSTRIAL ECOLOGY

The field of Industrial Ecology (IE) aims at analysing inter-connected value chains. It is the study of the flows of materials and energy in industrial and consumer activities, and of the effect of these flows on the environment. IE aspires to improve metabolic pathways of industrial processes and materials use, by dematerialising industrial output and creating loop-closing industrial ecosystems. The IE approach works on the macro level of our production systems and is often concerned with analyzing complex, multidisciplinary systems. The objective is to understand better how we can integrate environmental concerns into our economic activities. Each investigation defines the system boundaries and asks for optimisation of the particular system (Fet 2005).

In environmental problem-solving, focus has shifted from site focus, e.g. in achieving cleaner production at a local production site, to value chain focus (see figure 1.2.1). A value chain is product related, and a product's total environmental impact from cradle to grave may be evaluated through a Life Cycle Assessment (LCA). In an LCA, every step in the life cycle of a product (e.g. a building), the inputs (raw material, energy, land and water resources etc) and outputs (solid wastes and emissions to land, water and air) are calculated. The result will depend on what indicators are chosen and how they are weighted, and there is a range of different methods for LCA developed. However, as the concept of LCA conceives the lifecycle as a linear chain of events, the tool has so far not integrated reuse or recycling into its framework (Thormark 2001, pp. 42-43).

The philosophy of IE is inspired by natural systems, and the term *biomimicry* is used in explaining how biological processes can be set as a model, measure and as mentor for human challenges (Benyus 1997). Nature's production lines are not generating waste but nutrients for other organisms, and its structures are optimized both by using the least amount of materials in relation to its stresses and by being dynamic to changing needs. When prescribing solutions for our cultural acti-

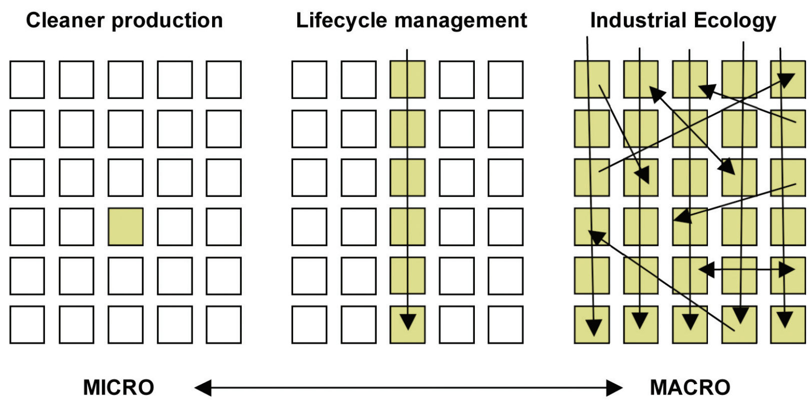
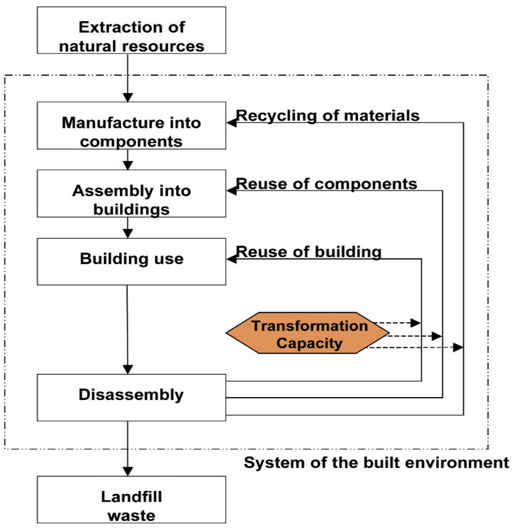


Figure 1.2.1: Different system approaches for environmental problem-solving: site focus, value chain and inter-connected systems. (Source: Fet 2005)

vities, the cleverness of nature can be a valuable source of reference.

A point of departure for this thesis is the mismatch between the technical lifetime and the service life of building components, and its negative environmental consequences. These issues fit well with the general philosophy of IE with its focus on optimizing industrial flows. Thinking about buildings and the construction industry as interconnected systems of real assets and mass-flows has no tradition in the business. Although buildings represent long-term relationships with the environment as well as with their users, the trade is generally characterized by short-term investments and thus risks of sub-optimizing goals. IE-principles can be used to illustrate and investigate the material flow in the building industry, and to identify what factors influence this flow. The achievements in Product Design and IE can be models for the building industry in the coming years. Instead of cradle to grave-thinking, the new slogan is cradle to cradle, or conception to reincarnation! (McDonough et al. 2002) With the quantities of construction & demolition waste in mind, there should be no reason not to consider measures such as take-back requirements also for the producers of building materials. More focus on the social responsibility of businesses reinforces this trend. When discussing environmental efficiency of constructions, the field of IE provides tools to monitor trends of development, and demonstrates the importance of holistic overall planning to avoid sub-optimization.

The recycling hierarchy shows the material flow through the system of the built environment, and its recycling possibilities (figure 1.2.2). It incorporates a number of more or less environmentally attractive end-of-life options that will potentially reduce the quantity of waste and pollution generation.



Recycling (or *downcycling*): Collection of products for separation into their base materials, which can then replace raw materials in the production process. Example: Second hand aluminium, used glass for mineral wool.

Reuse of components: Doors, windows, roof tiles etc. being simply used more than once for its intended purpose.

Reuse of building: Buildings being reused/ remodelled on original site or disassembled and moved.

Figure 1.2.2: The recycling hierarchy (based on Crowther 2003)

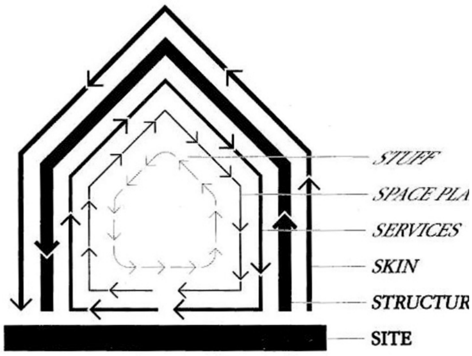
The diagram organizes the material flows of the built environment after hierarchic principles. From the point of view of conserving energy during manufacturing, reuse becomes preferable to recycling or *down-cycling*. Less processing means less energy spent, less emissions released and often also less transport included; hence less is the total environmental burden. The highest level in the hierarchy is actually maintenance because frequent care saves the building from deteriorating with a minimum of environmental (and practical) effort (Brand 1994). When building components and structures are designed for disassembly and reuse, it is viewed as beneficial for all the steps in the recycling hierarchy. This includes providing flexibility and ease of maintenance in the user phase, relocation or remodelling of whole buildings as well as ease of deconstruction.

LIFECYCLE PLANNING

”A building is not something you finish. A building is something you start” states Stewart Brand, author of the book: *How buildings learn* (Brand 1994). The book has become a key reference in lifecycle planning for buildings. It describes how all buildings undergo changes in their lifespan, changes that are most frequently not designed by architects. Therefore buildings should be planned so that they are able to adapt to future changes that we know will occur.

The term adaptiveness can be further elaborated as: *Generality,* about a structure that unchanged can adopt to different functions, *Flexibility*, about a structure that can easily change within its outer frames, and *Elasticity*, about a structure that can shrink or grow according to new functions. “Adaptable buildings” focus primarily on the benefits gained for maintainability and changing user demands, and flexible office space and structuralistic home planning are among the resulting outcomes. Even though these measures are not primarily geared towards environmental gain, the technical solutions may allow for salvage of building materials as well. Besides, space efficiency is viewed as an achievement of flexible design that also gives environmental benefit (Arge et al. 2002). However, the terms “adaptability” and “flexibility” are not necessarily synonymous with environmental efficiency. Since defining the overall environmental profile can be a complex exercise, it seems necessary to clarify the aims and criteria of each project so that “green” arguments are not used to substantiate measures that may fail to solve environmental challenges in the long run.

According to Stewart Brand, different parts of buildings change at different time rates. An adaptable building thus has to allow slippage between differently paced systems. Embedding the systems together may seem efficient when building, but over the time it is the opposite. "As a designer you should avoid such classic mistakes as solving a five minute problem with a fifty year solution." (Brand 1994) Lifecycle planning



Site is considered eternal.

Structure (foundation and load-bearing elements) lasts 30 to 300 years.

Skin (insulation and cladding) change every 20-50 years or so.

Services (wiring, plumbing, heating and ventilation) wear out every 5-25 years.

Space plan (inner walls, ceilings, floors and doors) change every 3 - 30 years depending on building function.

Stuff (furniture etc.) move around daily or monthly.

Figure 1.2.3: Time related building layers (Source: Brand 1994)

thereby gives a rationale for designing flexible buildings with time-related layers. In figure 1.2.3, it is visualized how different parts of buildings change at different rates.

This stratification of building components according to their turnover frequency is also interesting from an economical point of view. Traditionally most of the costs, and thereby also most of the environmental investments, entered into the structure of a building. This was true both for initial construction costs and for the building's total lifetime costs. During the last 100 years however, this relationship has changed. Today, during the lifecycle of a building, the costs dedicated to the fast changing building layers add up and surpass the costs of structure and foundations. The expensive and complex service and interior systems often utilized in contemporary buildings belong to the layers with the most rapid turnover (Fernandez 2003).

The theory of time-related building layers demonstrates the connection between the different building parts' operational tasks and their turnover frequency. The concept is frequently referred to in the core literature of this thesis, and is seen as a principal system that should be adopted by the construction industry (see. e.g. Fletcher 2001, Crowther 2003, Durmisevic 2006). However, not all constructions are designed as multiple layers, and the rationale for recommending this way of building is worthy of a discussion. Indeed, a majority of contemporary buildings are produced with a variety of function specific material components, but there are also historic building types that mainly consist of one material in a homogenous construction such as brickwork. Also, integrated functionality of constructions is seen in experimental housing of low-tech materials such as strawbales. A remaining issue for this thesis is the technical and architectural consequences involved in the choice of construction, investigated in the context of salvageability.

DESIGN FOR DISASSEMBLY

Design for Disassembly/Deconstruction (DfD) implies an optimization of construction methods and connections between components to facilitate reuse and recycling. DfD is also viewed as a strategy to facilitate maintainability and adaptability during the building's operation period. Thus through recommended measures DfD is believed to assist future environmental savings (Berge 1997, Thormark 2001, Sassi 2002, Crowther 2003, Durmisevic 2006) as well as reduce lifecycle costs (Chini et al. 2003, Sassi 2004, Durmisevic 2006). By striving to capture the value embodied in the existing building stock, the goal is to eliminate the mismatch between building components´ service life and technical life. Salvaged building material may then reenter the metabolism of the building industry independent of building type and function. Studies have also pointed out that DfD can meet market needs for flexiblility (Durmisevic 2006, IFD-programme) and provide social benefits (Chini et al. 2003, Sassi 2004). The research field of DfD provides basic information and has been an important point of departure for this thesis.

DfD research introduces and discusses guidelines that describe how to design reusable and recyclable buildings (Berge 1997, Fletcher 2001, Thormark 2001, Sassi 2002, Crowther 2003, Durmisevic 2006). Some of these principles are presented as behavioral statements that deal with general environmental goals, whereas others are more prescriptive for the design solutions. Also, the classification systems of the guidelines vary. The principles may be related to scale of application such as the choice of materials, the design of the construction and the detailing of joints and connections, or to the scenario of a given building: Will it be designed for adaptability, reuse, recycling or incineration? (Crowther 2003, Addis/Schouten 2004) The various sets of guidelines thus present the design strategies in different contexts, and this can be peceived as confusing. Therefore, as part of this thesis work, a clarification of the criteria was necessary.

DfD research has also developed general, however mutually diverging, methods for assessment. The terms used to express the affiliated goals are; *ease of disassembly* (Thormark 2001), *suitability for reuse/ recycling/ down-cycling* (Sassi 2002) and *transformation capacity* (Durmisevic et al. 2003b). However, in these tools, there is generally a weak connection to the specific guidelines described by the same authors. The method can become more transparent by applying the guidelines directly in the assessment of the desired characteristics. Therefore, for the use in the subsequent case studies, a transformation of the guidelines into an overall system that also includes an assessment tool is attempted.

Basically, the overall aim for all DfD research is expressed as material resource efficiency achieved through facilitating reuse and recycling. However, in the different sets of guidelines describing how to design reusable and recyclable buildings, aspects that relate to the processes of sorting, transport, new design and reassembly are usually also stressed.

Therefore, the use of the term *Design for Disassembly* as an overall heading can be perceived as confining and misleading. Generally, a discussion of terms seems relevant as part of this thesis. The intention for a new term is to express the aims described in the design guidelines more completly.

ARCHITECTURAL IMPLICATIONS

Although the development of lifecycle planning and DfD is first and foremost related to measurable benefits for the users and for the environment, the architectural interpretations of the concepts have several sources of reference. Historically, DfD has its roots in the construction of vernacular tents of nomads, and has further developed as an architectural discipline in pavilions for great exhibitions. With an obviously short service life expectation, they need to be designed for disassembly and potential moving. Both Joseph Paxtons Chrystal Palace from 1851 in cast-iron and glass and Shigeru Bans Japanese pavilion for the Hanover 2000 fair made of cardboard tubes and tensile roof invoke admiration for architectural and technological advances. However, only the latter has a clear environmental profile demonstrated in material choice and in the lightweight construction. For more examples of historic and contemporary architecture related to DfD, see e.g. Crowther 2003.

However, architects in general have been slow to accept and pursue the inclusion of environmental measures in their work. One reason that has been stressed is that the built examples have not been regarded as inspirational or as appropriate architecture according to contemporary design standards. Claus Bech-Danielsen (Bech-Danielsen 1998) discusses how the environmental efforts in architecture can be divided in two categories: On one hand, environmentalist movements are developed by grassroot groups taking direct action in their own neighbourhoods. On the other hand, environmental management is produced by planners who draw up overall plans applicable to many different places. According to Bech-Danielsen, the paradigm of sustainability requires the use of both the senses and the intellect as means of navigation, and unfortunately both categories fail to bridge this gap.

In the 1920s and 30s, as new building materials were investigated, the act of creating architecture upon the knowledge of the properties of the materials and of how the components were most rationally produced has been labeled a *tectonic approach*. (Beim 2004). The early functionalists proclaimed that technical premises were interpreted and expressed in the new design ideals, which thus demonstrated a new spirit. In the 1990s, as a reaction to post-modernist architecture, the tectonic approach was forwarded by Kenneth Frampton: In a situation where buildings are reduced to mere scenographic images, the connection between the material properties and architectural expression becomes fragmented and weak. Instead, tectonic architecture stresses structural and material coherence and probity, and the cultivation of materials and structures in a poetic way. Also historically, buildings are considered as ”things” rather than as ”signs” (Frampton 1990).

The different measures for environmental efficiency such as climate adaptation, temperature zoning, solar energy harvesting and natural ventilation have various implications for architectural design, and the interpretations can take on many shapes. Furthermore, it can help substantiating design concepts in a useful and meaningful way (Larsen et al. 2006, Monsen 2006). As with the implementation of the new technologies during the early functionalism, environmental considerations today can inform choice of materials, construction methods and detailing. Demountable expo-pavillions as well as a range of other examples of sustainable architecture in general show that architects are fully able of finding innovative and architecturally interesting solutions to technical and environmental challenges.

The studies by Bech-Danielsen place sustainable architecture in a theoretical framework, and thus represent a novel research effort. Sustainable building has so far had few connections to architectural theories, although the need for this is evident as the field is of emerging interest and by many regarded as the most important contemporary movement. According to Chris Butters, architects pursuing sustainable building have maybe been too pragmatic in their investigations of earth, water, energy and user participation, and neglected to provide a principal theoretical framework that places their work in a context of architectural history and philosophy (Butters et al. 2000, p. 171-178).

Questions to be asked in this context is what the specific architectural implications of the design measures of salvageability are, and more principally; how can these discussions eventually contribute to expanding architectural theory about sustainable design? In these discussions, it makes sense to use the tectonic approach. Within the rather limited scope of this thesis, I choose to use this term as a loanword from a maybe not so closely related research tradition, and investigate its usefulness in the context of sustainable building.

1.3 Contextual considerations

THE METABOLISM OF THE BUILDING INDUSTRY

The Norwegian building industry generates about 1,5 mill. tons of waste yearly from new construction, renewal of existing buildings and demolition. This represents about 15 % of the total amount of waste streams, which are growing. In 2004, about 38 % of the registered construction waste was disposed in landfill, 27 % was burned with energy recovery and about 18 % was recycled (Landet 2007). Fortunately, the percentual recycling is increasing, and some projects have achieved a degree of recycling at more than 90 %. New regulations for construction and demolition projects, introduced in 2008, now demand a minimum of 60% source separation, and a documentation of the waste streams. However, a very small amount of components are reused. The causes for this are complex, but the lack of transformation capacity in the design of buildings can be considered a prime hindrance.

A contextual diagram illustrates the system of material flow - or metabolism - in the built environment (figure 1.3.1). The building's transformation capacity can be viewed as a catalyst or driver for the material cycles in the system, making the internal loops more efficient. Other, external systems influencing the flows can be divided into socio-econo-

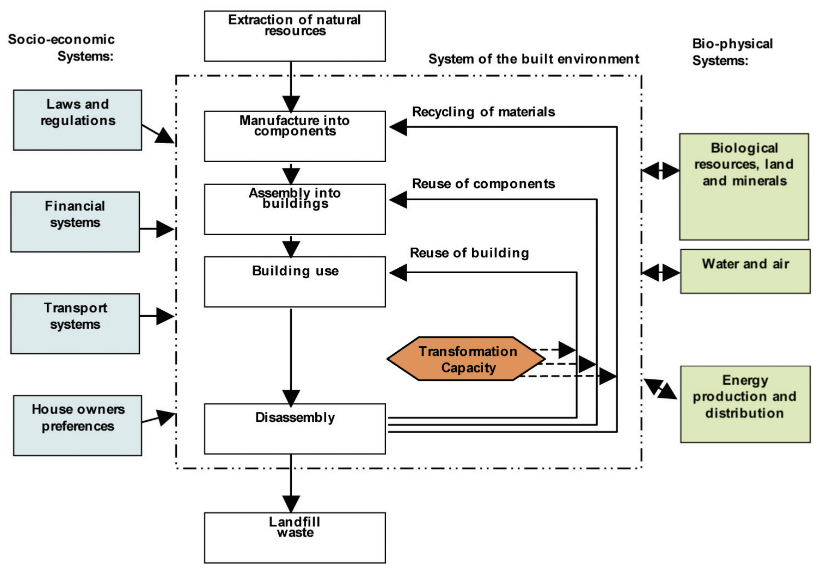


Figure 1.3.1: The contextual framework of the building industry (based on Crowther 2003)

mic and bio-physical systems. The socio-economic factors include laws and regulations (building code, landfill tax etc.), financial systems (deciding what is economically desirable), transport systems (important in assessment of eco-efficiency) and house owners preferences (life style and fashion). The bio-physical factors consist of the different types of natural resources that can provide raw materials for the building, of water and air, and of the energy production and distribution systems.

Different stakeholders give important input to this system. Builders and house owners may view it as beneficial to make the extra investment in a demountable structure. In the Netherlands, the national IFD (Industrial, Flexible and Demountable) Building programme states that the market demand for flexible buildings is increasing. People prefer to redo their homes according to shifting family situations rather than to move to another neighbourhood (IFD website: www.sev-realisatie.nl/ifd/ 2004). Laws and regulations controlling the waste streams have become more strict and are expected to become even more so in the next decades (Addis/Schouten 2004). Tax on landfills, pollution legislation and building codes put pressure on recycling activities. Regarding building material and component production, new solutions on product stewardship and extended producer responsibility might radically change the production and delivery of material goods.

There are different kinds of drivers in this system, and there are also hurdles - both real and perceived. Additional design and building costs can be a first hurdle. Other constraints related to the second hand use of materials are connected to warranty and insurance systems. "Using reclaimed products and materials is often perceived to increase the risk of failure to meet the required performance or durability of a building element. While such risks can be eliminated by testing and re-certification, prejudices may still remain." (Addis/Schouten 2004, p.70) People usually prefer new material to second hand, and it is always easier to continue well-known practice than to develop new routines. Nevertheless; testing and achieving renewed performance warranties represent real hurdles by supplying additional costs. Also, the cost of storing reclaimed products and transporting them to where they are needed should be accounted for.

The diagram describes a system in change. According to (Addis/Schouten 2004), the drivers for designing buildings for disassembly and reuse as well as the hurdles, are believed to change, maybe dramatically, over the next decades. This means that the buildings erected today will meet a different socio-economic climate when their service lives come to an end. "Few of the principal drivers are yet strong enough to motivate clients and construction teams to implement design for deconstruction. However, their potential influence during the life of buildings now being designed is already apparent." (Addis/Schouten 2004, p. 67) The diagram thus demonstrates the importance of the external framework in facilitating salvageability in the built environment.

For the purpose of avoiding developments that fail to meet environmental effieciency in the long-term, the measures must be coordinated.

THE ECONOMIC FRAMEWORK

The cost is generally an important framework condition for how buildings are being created. As earlier mentioned, design and building costs are often considered as an obstacle in achieving adaptable and salvageable constructions. However, in a long-term perspective, sustainable solutions may show to be financially advantageous. As pointed out by the Stern report (Stern 2006), global environmental threats like climate change require setting broad boundaries for the financial analyses, both geographically and in terms of period of time. Decision-making in a building project is usually based upon mere acquisition costs, but in order to make sustainable solutions financially viable, a lifecycle perspective must be used. This will influence thermal insulation standards as well as durability, maintainability and flexibility. With these intentions, lifecycle costing (LCC) was made mandatory for public procurements in Norway in 2001 (MD 2007). Although the LCC methodology is limited to economic calculations, and is insufficient in accounting for environmental, social and cultural assets involved in buildings, the hope is that it may help to focus on long-term sustainability (Cole et al. 2000).

The salvage of building materials was financially profitable in Norway in earlier times, just as it is in developing countries today. However, in the 1950/ 60s there was a shift in cost-consumption between materials and labour, where it no longer became profitable to economize material use by spending more time for design or for execution. For instance, instead of letting the engineer spend work hours on calculating various thicknesses of concrete slabs according to the specific load balance, as was usual practice in the 1920/ 30s, one now rather specified an even slab thickness that corresponded to the highest stress (Noach 1985 and personal communication with architecture historians Kerstin Gjesdahl Noach and Dag Nilsen 2008). This new practice naturally affected the resource use, as the highest stress in a complex construction always will demand the most materials. But also, as a consequence, this shift affected architectural design which lost an impetus for tectonic articulation.

The high costs of labour, together with high financing costs for building projects are reasons for the general high speed in the construction industry. Architects often work long hours to satisfy the builder's need for a tight time schedule, but are by no means the only disciplinary group that are under pressure. Unfortunately, the fast pace hampers proper design and construction as well as responsible deconstruction and waste-handling. In the end, fully marketable building materials are lost in demolition processes, not because there are no interested recycling contractors and distributors of reused materials, but because new building projects awaiting cannot allow the necessary amount of days - or not even hours - for disassembly and sorting before the site has to be cleared (Personal communication with Kenneth Urdshals at Stavne Gård Salvage Yard, Trondheim 2008). This speed itself, however economically justified, is devastating for the general resource use in the building trade.

As it can be pointed out that the economic framework affects the possibilities for achieving savageability in several ways, there are reasons to investigate the consequences of this framework. In this thesis, I choose to include discussions related to long-term material management and the hurdles for efficient resource use that the prevailing economic framework represents

THE CONCEPT OF SUSTAINABLE DEVELOPMENT

I will end this introduction with some remarks on the concept of *sustainable development*. In 1980 *The World Conservation Strategy* first gave currency to the concept. Stressing the interdependence of conservation and development, it emphasized that humanity, which exists as a part of nature, has no future unless nature and natural resources are conserved. It claimed that conservation cannot be achieved without development to alleviate the poverty and misery of hundreds of millions of people. A revised strategy called "Caring for the Earth" in 1991 defined the concept as "improving the quality of human life while living within the carrying capasity of supporting ecosystems" (IUCN/UNEP/WWF 1991).

However, the term has long been defined by the Brundtland commission's report from 1987, which then timely stated that our generation should take on the obligation of making sure that today's consumption of resources are not in conflict with the needs of future generations. Also, the report discussed the problem of poverty, as sustainable development demands a more equal distribution of the world's resources between people and between countries (Brundtland et al.1987). Today, some 20 years later, the present development is still definitely in conflict with the needs of future generations. The world has continued to experience an exponential growth in the use of energy and resources, a trend that has had severe impacts on the environment. Also, the goal of social justice is even further away from being achieved.

In the now conventionally accepted definition of sustainable development, the three parameters of ecological, social and economic needs are considered together, and these three "legs" form a common bottom line. This diagrammatic concept is often referred to in building projects, where economy is accepted as an equal parameter to ecology and social needs. However, as economy recurringly survives as the strongest argument in any discussion, the more compassionate values often crumble away in the process of design and building. Therefore, the concept of the *triple bottom line* needs a discussion. It can and has been taken to mean that if a project is not economic, it cannot be sustainable. From an environmentalist's viewpoint, the concept then misses the main point (Høyer 2008).

Brundtland's definition of the concept of sustainable development can be defined as belonging to the weak or *shallow environmentalism*. Here, the attitude of human beings towards nature is that nature should be protected, but a degree of trade-offs between ecological, social and economic assets are accepted (Shipworth 2007, Kohler 2006). This view contrasts with the strong environmentalism or *deep ecological awareness* as defined by writers such as philosopher Arne Næss. In the philosophy of deep ecology, nature is regarded as having implicit value disregarding the economic or social value it represents to humans (Næss 2005). Nature is thereby considered to be the basis of our culture and cannot be traded with other assets.

Recent literature on sustainable design reflects the view that shallow environmentalism may not be sufficient in solving the urgent global problems (McDonough et al. 2002, Reed 2007). A more radical approach emphasizes that sustainability, as currently practiced in the built environment, primarily works as an exercise in efficiency. Although it is a well-intended concept, *eco-efficiency* is pointed out as a failing strategy over the long term, because it does not reach deep enough: "It works within the same system that caused the problem in the first place, slowing it down with moral proscriptions and punitive demands. Prosperity remains unobstructed, and economic and organizational structures remain intact. It presents little more than an illusion of change. Relying on eco-efficiency to save the environment will in fact achieve the opposite - it will let industry finish off everything quietly, persistently and completely." (McDonough et al. 1998, p.4). Proposed alternative solutions include making a shift from sustainability to *regeneration*. Instead of just doing less damage to the environment, it is necessary to base development on the health of ecological systems. Regenerative design integrates environmental and social systems in processes that also imply conscious learning and participation. According to Reed, this shift involves a significant, but necessary, cultural leap for the consumer society (Reed 2007, p 674).

As the term itself cannot be blamed for its' connotations, maybe it is time for a redefinition of the concept of "sustainable development" towards the original meaning. Environmental, social and economic aspects could still build up the concept, but in a hierarchic order. The environment, including natural resources, would then constitute the base, and human actions manifested in social and economic activities would relate to this starting point. Quite simplified this would mean that industries, trade and financial frameworks must be based upon the possibilities and limitations of our natural resources, not the other way around.

1.4 Research Approach

ENVIRONMENTAL PERSPECTIVES AND SCIENTIFIC THINKING

According to philospher Arne Næss (Næss 1980), the transition from general cognitive activity related to information, knowledge and skills, to *science* consists of several interlinked steps. Increased generality of questioning, increased systematization and precision, detachment from practical use, increased institutionalization and, not least, increased disciplinary specialization mark this transition. However, science is also set in a philosophical framework, which is decisive for research in practice.

The philosophical framework of Western culture is rooted in the Age of Enlightenment and the following scientific revolution. Inspired by the machines of that time, thinkers like Bacon and Descartes explained the universe as a mechanical system, composed of monofunctional building elements. (Shapin 1999). In this world view, any piece of the machinery was seen as fragments operating separately and independently, and only the material aspects of natural phenomena was taken into consideration. The *teleological* view of the Earth as a living organism from medieval times slowly shifted to that of a machine (Capra 1986). The changes taking place in Europe in the 1600-1700s founded the science paradigm which has now characterized our culture for 300 years.

A reason for the environmental problems the world is facing today may be found in these *reductionist* definitions of science. Although a series of technological advances based on scientific research have represented improvements for many people, scientific reductionism has provided a logic of efficiency that has legitimated abuse and destructions of natural resources: By reducing complex eco-systems to single components, and single components to single functions, it allows for manipulation in a way that maximizes exploitation. Distortions of eco-systems are legitimized, regardless of whether that might destroy principal qualities such as clean water or the diversity of species. The Indian biologist Vandana Shiva states that "…reductionist science is at the root of the growing ecological crisis, because it entails a transformation of nature that destroys its organic processes and rhythms and regenerative capacities." (Shiva 1993)

In the 1960s and 70s, the environmental movement protested against politicians and industry and also against scientists, questioning our society's *linear* thinking and demanding greater holistic understanding (Næss 1980). In the efforts of meeting environmental challenges such as dispersion of chemical contamination and radiation, ozone layer depletion and global warming, the mechanical world view is now increasingly often seen as outdated. Reductionist thinking is frequently dismissed as inadequate for dealing with problems in an overpopulated, globally interconnected world. A demand for a radical shift in perception is forwarded, something which also involves accepting values as an integral part of scientific thought. In the writings of Fritjof Capra, these changes in science as well as in the social arena are referred to as a new paradigm shift, going from a mechanical to holistic worldview (Capra 1996). A common denominator is a focus on relationships rather than on objects.

Systems Thinking is a discipline for seeing the wholes and the structures that underlie complex situations (Fet 2005). Instead of linear causal connections, cyclical patterns of change are investigated. In the philosophy of Systems Thinking, notions like self-organisation, coordination and mutual dependency are important key-words. Systems Thinking has its roots in different scientific disciplines that developed during the first half of the twentieth century such as physics, psychology and biology. In all these fields scientists explored integrated wholes whose properties cannot be reduced to those of smaller parts. Systems Thinking completely breaks with the mechanical world view, and is linked with the progress of a global environmental concern. From the Systems perspective, the human actor is part of the feedback process, and this represents a profound shift in awareness. (Reed 2007)

Quite independent from the discussions concerning the environmental crisis, general criticisms of the reductionist tradition have been performed during the past decades. The book *"The new production of knowledge: the dynamics of science and research in contemporary societies"* (Gibbons 1994) describes traditional (reductionist or positivist) research as *mode 1.* Research in mode 1 is characterized as academic, discipline-based and investigator-initiated, and quality control is performed by peer reviews. As part of a general democratization process in Western societies, novel ways of scientific knowledge production are now becoming accepted and described as *Mode 2*. Research in Mode 2 can be context-driven, problem-focused and it is often performed in multidisciplinary teams. Furthermore, mode 2 accepts the researcher's role as non-objective and uses multidimensional quality assessment (Martin 2008).

Compared with Arne Næss' explanation of the development of scientific thought, these new definitions can be interpreted as representing a *step back* to more general cognitive activity. Mode 2 represents a development towards *decreased* institutionalization, *decreased* disciplinary specialization and *increased* contextualization. This can be seen as a reaction to fragmentation and loss of overview and holistic understanding. Also, a search for specific problem-solving and action is evident. The total of research papers and reports written has grown in numbers and volumes the past decades, not least in the context of the environmental challenges. In many cases, the lack of impetus for change is not the lack of knowledge, but is rather to be found in the political and economic systems. A new attitude is expressed in proverbs such as going "from know-how to do now" (introduced by Sofiestiftelsen 2007). These catchwords reflect a wish for a radical shift of approach that may be necessary in meeting the ecological crisis.

ARCHITECTURE AS A MULTIDISCIPLINARY FIELD

For the purpose of linking the research approach with the field of architectural design, I will discuss the multidisciplinary nature of architecture. In general, practicing architects are exposed to information and knowledge from different areas of expertise, and this is seen as an obvious and inevitable part of their work. As buildings and building production have increased in complexity, these specialist fields have grown in number, a fact that has led to an expansion of the architects' expected knowledge. The issues of sustainability add to this trend.

According to *Vitruvius*, the roman writer, architect and engineer active in the 1st century BC, architecture can be seen as a synthesis of functional, technological and aesthetical qualities. A successful building

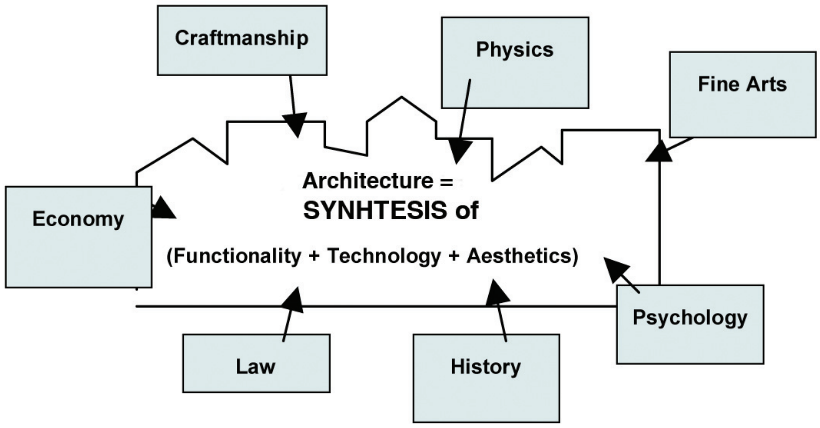


Figure 1.4.1: Knowledge fields important to architectural practice

depends on the fulfilment of requirements from all these three foundations. Functionality, technology and aesthetics are in turn connected with a range of knowledge fields as illustrated in figure 1.4.1. Vitruvius' view is still valid for buildings today, and the architectural design process can be regarded as a complex and iterative trade-off process between different demands.

The original meaning of the word *architect* is "leading craftsman". In other words, the architect of a building is expected to have elementary knowledge from all the professional craftsmen contributing in erecting a building, such as carpenters, brick-layers, painters and plumbers. Today, however, the cooperation with these specialist fields is more commonly performed through consulting engineers. The architect usually coordinates the design team and is responsible for the contact with the client. Also, the architect is expected to keep updated on general conditions such as developments of building materials and products and requirements regarding building approval and codes. The ideal architect is in many ways a ”renaissance person” who displays multi-disciplinary knowledge. In addition, a capability for collaboration with practitioners from other disciplines is required. Both these capacities can be described as multidisciplinary skills (Melhuus Hojem 2008).

The fact that the architectural profession is broad and multidisciplinary is reflected in architectural research, which is conducted in areas of social sciences, humanities and technology. Specific aspects about buildings are analyzed, aiming at bringing these contributions to the benefit for architectural practice (Mo 2004). Although architecture is also regarded as a field with its own knowledge, theories and methods, much of this research has been carried out within the scholarly tradition belonging to an adjacent discipline. For example: Studies in energy efficient buildings have typically been performed within the traditions of technical engineering, whereas studies in city planning have been performed within the traditions of social sciences. Although methods developed within all these traditions may be employed within the scope of “architectural research”, usually one disciplinary approach is pursued for each study.

However, the core of architectural practice is a synthesis activity, actually more closely related to holistic thinking than single-disciplinary analyses. Few studies yet explore the full potential that the architects possess as multidisciplinary professionals. This potential becomes particularly relevant in the context of environmental challenges, which, as described, may benefit from a holistic approach in problem-solving.

QUANTITATIVE AND QUALITATIVE RESEARCH

Basically, research can be perceived as investigations with the purpose of new knowledge production. To be professionally recognized, these investigations need to be systematically and transparently organized so that the results may be validated later by other researchers. Depending on the research field and topic, there are naturally different kinds of information or data to be collected, assessed and reported on. Depending on what kind of data and the type of research question, various methods can be appropriately applied (see e.g. Yin 2003, p. 5, Groat et al. 2002).

Generally, one may distinguish between quantitative and qualitative research. The quantitative methods are typically used in traditional scientific theory testing, whereas qualitative methods are known from the humanities. In the social sciences, both approaches can be relevant. Both quantitative and qualitative methods have their strengths and pitfalls. Whereas quantitative analyses can map cause-effect chains and derive at generalizations about specific problems, qualitative analyses focus more on understanding processes and relations. Qualitative methods are appropriate in investigating complex, "real-world" problems in a holistic way, and a structured debate can be regarded as a valuable outcome (Groat et al. 2002, Crowther 2003).

A common objection concerning qualitative research is that it is more prone to bias than quantitative research. Within a positivist science tradition, qualitative methods therefore usually require more explanation and theoretical support than the quantitative methods which are seen as more or less self-evident. However, also in pure quantitative experiments, the scope of study, the choice of assessment criteria and the weighting of each variable can be manipulated to fit the supposition of the researchers. Therefore, in each case, the validity of the research should be assured by designing systematic studies that are transparent to the readers, and by undergoing quality assurance such as peer-review processes.

Although quantitative and qualitative methods represent different research procedures and traditions, they can be combined and often are in typical case-study research. According to social science researcher Sigmund Grønmo, many weaknesses of quantitative data can to a great extent be compensated for by the strengths of qualitative data, and vice versa. Principally, there are four different modes of integration: 1. qualitative data are used in designing a quantitative study, 2. qualitative data are used in discussing a quantitative study, 3. quantitative and qualitative methods are used in parallel to study the same phenomenon, and 4. qualitative data are analyzed quantitatively (Grønmo 2004, p. 209-214). Various modes of integration are used in this thesis, and will be described in the next sub-chapter.

1.5 Inquiries and methodology

BROAD PERSPECTIVES AND NARROW FOCUS POINTS

This thesis is based upon an understanding that global environmental challenges demand Systems Thinking and long-term perspectives. Also, as architecture is seen as a complex field that draws on various traditions of research, it is natural to set the work in a broad context and to use a multidisciplinary approach.

The overriding scope is, as stated earlier, to investigate building methods that may contribute to solving a set of environmental challenges in a long-term perspective, and to explore ways to expand the applicability and transfer the concept of salvageability to contemporary architectural practice. The aim is to contribute to new understanding in this field, both at the level of design, and at a more general level of the building trade where the drivers and the hurdles for environmental considerations are complex and interconnected. The goal is more holistic knowledge, which is required in solving the environmental challenges.

The investigations are results of a patch-work of inquiries, and are generally explorative in nature. To reach the goal of more holistic knowledge, the field is looked at from different angles, and various kinds of research methods are used in an integrated research design. Embedded in a holistic framework of Systems Thinking, a combination of quantitative and qualitative analyses, literature review, case-studies and critical reflection constitutes the strategy.

There are definitely challenges and risks involved in pursuing a multidisciplinary approach in a PhD project. Whereas the critical characterization of the specialist may be simplified as somebody knowing "more and more about less and less", the opposite critique can be positioned towards generalists who know "less and less about more and more". Particularly in a situation where there is not a team involved, but where an individual generalist does "border walking" and simply receives information from adjacent disciplines, there are chances that the studies will not become sufficiently robust and acknowledged within any of the disciplines. I have seen the use of various methods as a way of mapping different possibilities and thus also as an important aspect of my training as an architectural researcher.

Although a broad perspective is attempted, certain focus points are selected. The questions are chosen to fill in the "blank spaces" of earlier research. These focus points are seen as "acupunctural" spots, as they can hopefully contribute to energize the debate. Throughout the studies, there has been an attempt to keep one eye on the overall perspective and simultaneously to pursue one question at the time in greater depth. The more specific research questions of this work are structured into three areas of inquiry, headed under the question words "Why", "How" and "So what". In the following, an introduction to these focus areas is presented, and the methodology discussed.

QUESTIONING "WHY"

This first introductory study aims at throwing light on the environmental rationale of *design for disassembly/ deconstruction* (DfD). The question word *why* thus reflects the overall scope. However, there are many ways in which this problem can be adressed:

First it seems like an obvious fact that we may achieve environmental and maybe also economic gain from designing a building for adaptability and salvageability *if* these capacities actually are used later. In the context of material reuse, the argument is validated if the technical lifetime of a component is longer than its' functional lifetime in a building. If salvage is planned for, a second service life of the components is feasible. In other words: the need for salvageable design is connected with the turnover of the components. Forecasting the possible turnover of both building and component layers before designing is generally a strategically important step in life cycle planning.

A second argument, which is chosen to be explored in this study, involves another mind-set; the environmental load of producing building materials should be credited with usability over time (Berge 2005). Stating that materials with a high environmental impact may be justified if they have a long lifetime reflects a normative attitude, which is part of the environmental agenda. Furthermore, since a long component lifetime presumably also involves changes during remodeling and rebuilding, high environmental investments call for a design that facilitates both renovations and potential new service lives for the components.

The main question is therefore broken down into more specific questions that are researchable:

- *What technical lifetime of building structures can be seen as environmentally justifiable with regard to their material composition?*
- *Considering the average turnover of buildings, can the results from these calculations give some indications about the need for DfD for different material groups?*

The research design for this study can be described as a quantitative study that is performed within a qualitative study. It combines using strategy number 1 and 2 in (Grønmo 2004): Qualitative data are used in both designing and discussing a quantitative study. The quantitative assessment is used to substantiate the argument of environmentally justifiable lifetime, and to visualize the consequences of this mind-set. In the end, a discussion relates the findings to the initial question of environmental rationale.

The assessment that is performed uses a simplified method for calculating the environmental impact of ten different wall constructions. The indicator used is greenhouse gas (GHG) emissions, and the chosen functional unit is 1 m^2 of complete exterior wall. Each case represents promoted materials for environmentally sound solutions. A construction in wood framework with an average lifetime of 50 years is chosen as a reference unit, and the resulting impacts from the other wall constructions are benchmarked against this figure.

GHG emissions measured in CO_2-equivalents are used as a single indicator for environmental considerations. There are several reasons for this. Firstly, climate change is an urgently important matter that it is no longer possible to overlook. Also, the use of GHGs is gaining ground internationally as an overall indicator, which makes it convenient when relating to other studies. A shortcoming of the indicator however, is that it does not show environmental damage caused by toxins, nor does it valuate loss of biological diversity.

The study considers only wall constructions and their environmental impact during material extraction, production, and transport to building site. Each case has a U-value=0,20 (W/m^2K), but the potential effect of heat storage in the materials is not considered. Similarly, a possible gain from CO_2- storage in biomass materials is not included in the calculations. CO_2- storage would certainly give large effects if included, but since there is little consensus on a method of calculation, it is left out. The analysis does not consider varying maintenance requirements, and it neither includes financial assessments.

The GHGs are calculated for each separate layer of the walls and summarized. The transport distances from production to building site are estimated as average for Norwegian building materials. Data on GHGs for the respective materials are mainly obtained from the Norwegian Building Research Institute (SINTEF Byggforsk).

After the quantitative analysis, a discussion explores the concept of *environmentally justifiable lifetime*, and what consequences the results may get for the choice of materials and types of construction.

QUESTIONING "HOW"

The overriding research question is:

- *How can building design facilitate future deconstruction and salvage of materials?*

This question involves both how to design buildings and components, and how to assess the design with regard to the desired objectives. The topic is investigated in two steps.

In the first step, the existing design guidelines on "Design for Disassembly" (DfD) are analyzed. The aim is to create a structured and consistent base of information to be used in different contexts in the rest of the thesis work. Also, the study aims at establishing an assessment tool. Although earlier studies have introduced various assessment methods, there is generally a weak connection between the specific design guidelines and the assessed parameters. The derivative questions for this study are therefore:

- *How can the guidelines of DfD be operationalized into an assessment tool?*
- *What are the determining factors for this tool?*

The method is literature review and critical reflection. The study naturally builds upon relevant literature on DfD. Existing guidelines from eight different studies are reviewed, as well as assessment methods from three studies. The use of critical reflection implies an intellectual exploration that leads to the proposed new systematization. By studying the various systems of guidelines and assessment methods and their ways of characterizing and classifying principles, a transformation of the systems is set forth with the purpose of finding a new logic order. The study is based upon open argumentation, and hence regarded as purely qualitative.

In the second step, two case-studies are performed. The derivative questions for the case-studies are:

- *What are the possibilities and limitations for building components of different material groups with regard to DfD (or salvageability)?*
- *Should different materials be assessed with the same or with different criteria?*

The framework for both case-studies is the new systematization of guidelines resulting from the previous study. Firstly, the matrix is used as an assessment tool. The method of the assessment corresponds to point nr 4 in Grønmo 2004; qualitative data are analyzed quantitatively. The case study objects, consisting in the first study of single components and in the second study of complete constructions, are qualitatively evaluated with regard to each strategy in the matrix, but reported quantitatively by a score. According to Grønmo, this type of procedure is first and foremost suitable for communication of qualitative results. The assessment is performed by the authors and is thus subject to personal interpretations. However, the study endeavours to meet the requirements of structure and transparency to assure the research quality. The method is more closely described and commented upon in the papers of chapter 3 "HOW" and in sub-chapter 5.3; Answering "How".

Secondly, the criteria of the new systematization are used as headings for the discussions. The criteria summarize the core points of the guidelines and are expressed as general performance standards. The framework for both the assessments and the following discussions are thereby informed by the new systematization, which serves as a unifying base of information.

The investigations are pursued for two different building materials: Massive wood and brickwork. The choice of these material types is first and foremost supported by the environmental rationale. The idea is that instead of focusing on the worst case material groups related to environmental impact, it is more interesting to pursue the materials with the best overall opportunities. The raw materials wood and clay are plentiful and wide-spread in Norway, and have good chances to continue as sustainable options. Moreover, massive wood and brickwork have high potentials regarding salvageability, however in different ways, as described below.

Massive wood has all the environmentally beneficial properties of wood, like being a renewable material, often locally produced, and also in contributing to a healthy indoor environment. In addition, since composed of large volumes of biomass material, massive wood can mitigate climate change through *carbon storage* (Wærp et al. 2008, Gielen et a. 2000). However, to make carbon storage a credible alternative, a long component lifetime must be expected. The most commonly used massive wood components today are not designed for a second service-life.

Bricks, on the other hand, have a considerable energy consumption related to production, but are durable and easy maintainable. Bricks are therefore a good example of a building unit suitable for a long life, a point well documented throughout history since bricks are known to endure reuse in several generations of buildings. The development of brick constructions during the last 100 years, however, has resulted in unsalvageable designs.

A second reason for choosing massive wood and brickwork for the cases-studies is that both material types have long traditions as building materials in Norway. Timber has been an obvious choice for buildings since prehistoric times, and bricks have since the 1200s supplemented and gradually replaced natural stone. Thus, the choice of material types enables a connection to a parallel study of historic building traditions. The functional units for both case-studies are chosen so that the compilation can represent a historical development. The selection is composed of one historical case, two contemporary and commonly used cases as well as two newer or more experimental cases. In this way, comments on the developments of principles and practices can follow a chronological order.

Reuse of components is particularly focused, and there are several reasons for this. Reuse is considered to be the best environmental option according to the recycling hierarchy (see figure 1.2.2). Also, reuse of whole components represents an "intelligent" level compared to the recycling option because the design of joints and general implementation demand careful consideration. For the same reason, design for reuse is also the most interesting option to pursue as an architect. As measures for facilitating reuse may be integral parts of both traditional building methods and modern designs, this choice gives an opportunity to study architectural detailing in the context of historical development.

The case studies are, however, different in the way that the first study explores single components whereas the second study explores complete constructions. This gives the opportunity to investigate the relevance of the method in different contextual situations.

QUESTIONING "SO WHAT"

The research question is:

• *What are the architectural consequences of salvageability?*

The aim is to couple the findings of the first investigations with the field of architectural design. The study discusses in what ways the criteria for salvageability, as measures for sustainable construction, can be integrated as an innate part of the design process.

Generally, there are several possible starting points for this integration. Measures for sustainable construction, such as thermal insulation standards and waste reduction requirements, are implemented through regulations in the building code and through financial incentives. These are important policy instruments in gearing the overall building activity towards more sustainable solutions. However, regulations do not principally aim at a change of mind-set, and are more often perceived as obstacles in achieving good design solutions.

The idea and the impetus to pursue this question came during discussions with architect colleagues. An important motive was to bring research results closer to practical design work and to the sphere of interest among architects. As there seems to be significant interactions between the guidelines for salvageability and some basic elements of creating architecture, the overriding hypothesis for this study is that the demand for salvageability of building materials may be seen as a positive driver for architectural design. The study explores in what ways this field of knowledge may influence building practice and architectural expression.

Sustainable architecture has so far had few connections to principal theoretical frameworks that place these buildings in a context of architectural history and philosophy. However, it is acknowledged that the different measures for environmental efficiency have various implications for design. As with the implementation of the new technologies during the early functionalism, can environmental considerations today inform choice of materials, construction methods and detailing. The concept of tectonics implies using technological parameters as a source for design, and in this context the concept is expanded to include measures for a responsible resource use. The tectonic approach is used in discussing architectural implications of the design guidelines for salvageability. More principally, these discussions can help linking tectonics to architectural theory about sustainable design.

The study is open-ended and explorative in nature, and is based upon a purely qualitative research design. In principle, it can be categorized as a phenomenological investigation in the sense that it deals with a subjective experience (Mo 2003, p. 60). The strategies are coupled with personally selected architectural examples as well as with my personal knowledge as a practicing architect. However, as in the earlier papers, the discussion is structured according to the criteria for salvageability. The criteria thus form the framework of the study, and this strategy may increase the transparency of the research. The use of the criteria also relates this last study to the previous papers, and thus substantiates consistency of the thesis.

THE WORKING PROCESS

The idea for this research project was conceived and forwarded by the Norwegian Directorate for Cultural Heritage, which also partly supported it financially. The first heading for the project was "PLUKKHUS", meaning a house that can be taken apart. Plukkhus corresponded to the various building methods in vernacular traditions that facilitate relocation or reuse and also to the "Design for Disassembly" (DfD) - approach. However, as increasing amounts of literature on DfD appeared, the number of possible research problems that were not yet investigated was narrowed down.

The research design was presented at an open faculty "hearing" spring 2005. Comments given from the participants were valuable for the further process. Particularly, the unsurprising and somewhat provocative question from some of the architects of "what has this got to do with architecture?" was later actually pursued in the last article. Generally, colleagues both at the faculty and externally have generously shared their ideas and approaches on this subject.

The original research plan included a greater number of case-studies. For several reasons, I decided to give priority to only two case-studies after the method of comparison was worked out in chapter 3 ("HOW"). I considered that the two case-studies supplemented each other in various ways, as they shed light on different aspects on salvageability as well as on different aspects of the method itself. Therefore, more case-studies would probably not give considerable extra information. Instead, I considered that spending more time on the related topics in chapters 2 ("WHY") and 4 ("SO WHAT") would give more interesting and valuable contributions to the field.

Quite early I decided to base the thesis upon articles. The reason for this was two-fold. Firstly, I saw paper-writing as a way of structuring the work so that the load was distributed more evenly throughout the PhD-period. Deadlines for relevant conferences and journals have helped setting timeframes for the work. Secondly, I regarded publishing and presenting articles as a way to gain feedback. Peer-review processes in connection with both journal articles and conference papers have generally given relevant and encouraging support, and these processes have also helped assuring the research quality.

The writing process itself has been an important working method. Writing has often activated the ideas as well as the problem-solving and has been a way to push the discussions. By structuring the articles, the structure of the research itself has also taken shape. Valuable guidance in carrying out the research and in language vetting has been offered by my supervisors, and thus they are included as co-authors. This is common procedure in my department. However, I am the main author of all the articles, have done all the writing, and take the full responsibility for the scientific contributions as well as for any shortcomings.

OVERVIEW OF PAPERS

The studies are described in five papers, connected to the three areas of inquiry as illustrated in figure 1.5.1. A list of the papers is presented below.

Paper 2.1: Lifetime and demountability of building materials

Authors: Anne Sigrid Nordby, Anne Grete Hestnes and Bjørn Berge. Published in: Mourshed, M. (editor) (2006) Proceedings of the Global Built Environment (GBEN) Towards an Integrated Approach for Sustainability (8 pages). Presented at: GBEN conference in Preston, UK 11-12 September 2006, where it was awarded a prize for the best PhD-paper.

This first study aims at substantiating the environmental rationale for facilitating reuse and recycling. A quantitative analysis of greenhouse gas-emissions from the production of ten exterior wall constructions is performed, and the normative relationship between salvageability and environmental impact of building materials is discussed. A Norwegian article based on the same study (*Byggematerialer; klimabelastning, miljømessig forsvarlig levetid og design for gjenbruk*) was published in the journal of BYGGEKUNST (now "ARKITEKTUR N") No. 01-2007, and is included as an attachment.

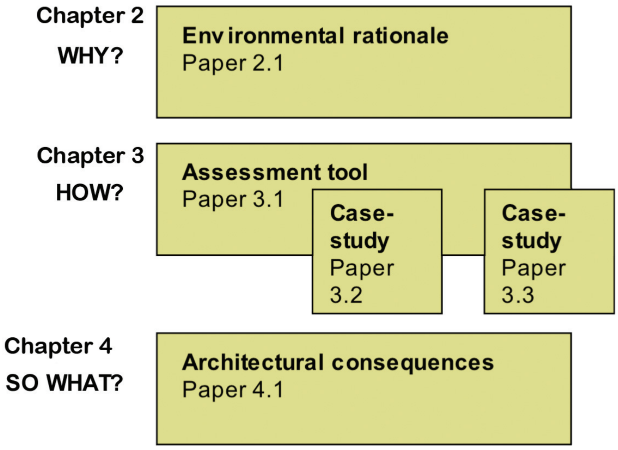


Figure 1.5.1: Overview of papers

Paper 3.1: Salvageability of building materials

Authors: Anne Sigrid Nordby, Bjørn Berge and Anne Grete Hestnes. Published in: Braganca, L. et al. (eds.) (2007) Sustainable Construction, Materials and Practices - Challenge of the Industry for the New Millennium. pp. 593-599. IOS Press. Presented at: Sustainable Building conference in Lisbon, Portugal 12-14 September 2007.

In this study, existing research on DfD is analyzed, and the selected design guidelines are structured in a principal matrix that may be used as a tool for assessment. Also, the term *salvageability* is introduced.

Paper 3.2: Reusability of massive wood components

Authors: Anne Sigrid Nordby, Bjørn Berge and Anne Grete Hestnes. Published in: Braganca, L. et al. (eds.) (2007) Sustainable Construction, Materials and Practices - Challenge of the Industry for the New Millennium. pp. 600-606. IOS Press. Presented at: Sustainable Building conference in Lisbon, Portugal 12-14 September 2007.

This first case-study assesses the reusability of five massive wood component types by using the assessment matrix. Also, the background and the practical, technical and architectural consequences of the design measures for each criterion are explained and discussed.

Paper 3.3: Criteria for salvageability: the reuse of bricks

Authors: Anne Sigrid Nordby, Bjørn Berge, Finn Hakonsen and Anne Grete Hestnes. Published in the journal BUILDING RESEARCH & INFORMATION (BRI) 2009, Vol. 37:1, pp. 55 - 67.

The second case-study investigates the salvageability of brickwork. The criteria are used as headings for discussing the single brick itself, and the assessment matrix is used for a comparison of five complete exterior wall constructions.

A Norwegian essay (*Tegl: god miljøprofil fordrer ombrukbarhet*) based on the same study is accepted for publication in a new book about masonry to be printed by Gyldendal in 2009, and is included in the attachments.

Paper 4.1: Salvageability: Implications for architecture

Authors: Anne Sigrid Nordby, Finn Hakonsen, Bjørn Berge and Anne Grete Hestnes.
Published in the journal NORDISK ARKITEKTUR-FORSKNING (Nordic Architectural Research) 2008, Vol. 20, No. 3.

This last study explores the architectural consequences of the design strategies for salvageability. The framework is based upon the predefined criteria, and the concept of tectonics is used as a tool for the investigation. Building examples from past and present are pointed to when discussing the principles.

1.6 Vocabulary

Most of the terms in this thesis are based upon common definitions used in the DfD-literature. The terms are explained in the list below, which is ordered thematically. The last three terms are not commonly used, but are introduced and further explained in 1.1 Preface; "Scope of thesis" and in 2.1 "Lifetime and demountability of building materials".

Reuse *(no: ombruk):* New utilization of a product in its' original form.
Recycling *(no: materialgjenvinning):* Processing waste materials to produce derivative products.
Downcycling: Recycling for a purpose with lower performance requirements than original.
Energy recovery *(no: energiutnyttelse):* Incineration of waste to generate energy.
Primary material *(no: primærmateriale)*: A material whose production has involved extraction from natural reserves.

Deconstruction *(no: selektiv el. miljøriktig riving):* A process of carefully taking apart a building, with the intention to maximize reuse or recycling of components and materials, and to minimize landfill.
Demolition *(no: konvesjonell riving el. demolering):* A process of reduction of a building, without necessarily preserving its components, and where materials primarily go to landfill.
Design for Disassembly/ Deconstruction (DfD) *(no: Design for gjenbruk el. prosjektering for ombruk og gjenvinning (POG)):* Optimization of components and construction methods to facilitate future reuse or recycling of materials.

Adaptability *(no: tilpasningsdyktighet)*: The ability of a structure to be easily altered to prolong its lifetime, for instance by addition or contraction, to suit new uses or patterns of use.
Flexibility *(no: fleksibilitet)*: The ability of a structure to be easily rearranged within its original frame.
Generality *(no: generalitet)*: The ability of a structure to be easily used for new purposes unaltered.

Service life *(no: levetid)*: Expected or actual lifetime of a component or a building, may be confined by functional, technical, economic or esthetic reasons.
Functional lifetime *(no: funksjonell levetid)*: The time in which a component or a building is usable, or in actual use, for one purpose.
Tecnical lifetime *(no: teknisk levetid):* Lifetime of a component or a building related to technical durability.

Sources: Addis et al. 2004, Leland 2008, Rognlien 2002, Thormark 2001

Salvage *(no: gjenbruk)*: Retrieve or preserve building materials from destruction, for utilization through reuse or recycling.
Salvageability *(no: gjenbrukbarhet)*: The ability of a structure to be salvaged.
Environmentally justifiable lifetime *(no: miljømessig forsvarlig levetid):* A service life (of a component or a building) that defends the environmental load embedded in the materials.

why 2.0

2.1
Lifetime and demountability of building materials

Anne Sigrid Nordby
Anne Grete Hestnes
Bjørn Berge

Published in:
Mourshed, M. (editor) (2006) Proceedings of the Global Built Environment (GBEN) Towards an Integrated Approach for Sustainability (8 pages)

Presented at:
GBEN conference in Preston, UK 11-12 September 2006.

Abstract

The scope of this article is to discuss the environmental rationale for demountable design as one of the measures for achieving a better material resource management within the building trade. Design for Disassembly (DfD) implies optimization of construction methods and connections between components and is viewed as a strategy to facilitate maintainability, adaptability, and end-of-life material salvage (Berge 1996, Fletcher 2001, Thormark 2001, Sassi 2002, Crowther 2003). For the considerations of the practical application of DfD, scenario based predictions are viewed as a prerequisite (Brand 1994, Durmisevic 2003). As a supplement to scenario-predictions, a second mindset is presented. The assessment of a construction's need for flexibility is suggested to mirror both the knowledge that different building materials charge the environment with a certain amount of impact generated through extraction and production, and also the fact that most building types are exposed to increasing turnover rates. The underlying assumption is that high impact materials may be justified by a long lifetime, however they should be prepared for probable alterations. An analysis on environmental load of 10 wall constructions serves as a support for introducing the concept of environmentally justifiable lifetime. The comparative results reveal large differences in impact between the construction materials, and subsequently large differences in the need for demountable design. The goal is to establish an understanding of the relationship between building materials' embodied environmental load and their technical lifetime, and through this reason for a material specific need for DfD.

Introduction

MATERIAL RESOURCE MANAGEMENT

The waste generated by construction and demolition of buildings (C&D waste) represents a main part of the total waste streams, which are growing. About 80 % of Norwegian C&D waste is disposed in landfill, 10 % is burned and only 10 % is reused (NABU 2003, BLF 2005). One important parameter for the minimal reuse potential is the design of building constructions. We have moved from utilizing a few, well known building materials to several 100 000s, composed of differently processed materials and a range of additives. Furthermore, building components of different materials and qualities are often permanently fixed to each other, and the service systems are integrated in the constructions. Demolition and landfill, possibly incineration or crushing into fill material, is then the only alternative even when only one of the components has served its function. We produce buildings designed for demolition.

The trade is also characterized by short-term thinking, and turnover is increasing rapidly. The poor resource management has negative environmental consequences in both ends of the material flow. The pressure on new raw material is increasing as waste handling is becoming a major issue with growing landfills and toxic emissions. On their way from cradle to grave, the processing and the transport of materials consume large amounts of energy.

In spite of these negative trends, there are examples of ”recycled buildings”, meaning buildings made of materials from deconstructed houses. One obvious motivation is economy, in other situations the reuse of components may be regarded as an additional quality. Also recycling of scrap iron and crushing of concrete for road construction have long been common practice. However, there are large differences in the existing building stock when it comes to recyclability. Most post-war buildings are not designed to be taken apart for reuse or recycling, whereas older buildings actually were. Brick buildings with lime mortar commonly used 100 years ago are highly recyclable. Also traditional Norwegian log houses can be said to be designed for disassembly and reuse. Log constructions are prepared for both replacements of units, remodeling and relocation. Unfortunately we have not been able to bring these design principles into the modern building industry.

DESIGN FOR DISASSEMBLY

Reality shows that different parts or layers of a building are changed at different rates. Whereas the structure of a building can last for 60 years, exterior surfaces may change every 20 years and service systems such as wiring and ducting may wear out as soon as after 7-15 years. Therefore, an adaptive building has to allow slippage between differently paced systems (Brand, 1994). Used building structures are often sent to landfill independent of their technical quality because a potential second hand use is not financially profitable. We have a mismatch between the often long technical lifetime of components and the often short service lives of a building or of a building layer. This mismatch may be perceived as a design problem.

Various researches have introduced and discussed the term Design for Disassembly (DfD) as a main target in reducing the environmental impact of building constructions (Berge 1996, Fletcher 2001, Thormark 2001, Sassi 2002, Crowther 2003). DfD implies optimization of construction methods and connections between components and is viewed as a strategy to facilitate both maintainability, adaptability, and end-of-life material salvage. DfD may reduce lifecycle costs as well as environmental impact. Given durable and optimally designed components and a building industry oriented towards reuse and recycling, infinite component lifetimes are viewed as feasible.

ENVIRONMENTAL RATIONALE

Historically, Design for Disassembly has been implemented in the vernacular construction of nomadic tents, in pavilions for world exhibitions, and in futuristic projects by innovative architects like Buckminster Fuller and Archigram. Today a main motivation for DfD is based on environmental concerns. However, will a strategy of DfD necessarily have an environmental rationale for all types of buildings and for all materials? One side of the coin is obviously expected turnover rates, which is already well recognized as a parameter of assessment. The need for demountable design may be determined by scenario based predictions (Brand 1994, Durmisevic 2003). If the predictions imply high turnover, we will have both environmental and economic gains from DfD.

As a supplement to scenario based predictions, a second mindset is presented. The assessment of a construction's need for flexibility is suggested to mirror also the knowledge that different material categories represent various stresses on the environment. Through extraction, processing, transport, and as waste, building material consume raw material, energy, land and water resources, and generate solid wastes and emissions to water and air. Materials with a high environmental impact may be justified if they have a long lifetime. Financially, when thinking long term, it is regarded as worthwhile to invest in a durable material in spite of a long pay-back time. Similarly, for the environment, long lasting materials give advantages because a long lifetime means that there will be less pressure on new material resources and that wastes will be reduced.

However, since statistics show that buildings change at an ever faster pace, building components and materials produced for long technical life with a high environmental investment should be prepared for the journey. They should be designed so that both renovations and potential new service lives are facilitated. The method presented here places environmental impact of building materials as the point of departure for a calculation of expected lifetime, or pay-back time. Considering the average turnover of buildings, the results from these calculations give indications about the need for flexible structures.

Analysis

METHOD

The environmental load of ten different wall constructions is calculated. The functional unit chosen is 1 m^2 of complete wall, in each case with a U-value=0,20 (W/m^2K) and each representing promoted alternatives for environmentally sound solutions. Five different construction materials are used in two versions, that is: wood framework, massive wood, strawbales, bricks, and aluminium framework. The construction materials are supplemented with varying layers of insulation and weather proofing. A construction in wood framework with an average lifetime of 50 years is chosen as the reference unit. The resulting impacts from the other wall constructions are benchmarked against this figure.

Greenhouse Gas (GHG) emissions measured in CO_2-equivalents is used as a single indicator for environmental considerations. There are several reasons for this. Firstly, climate change is an urgently important matter that it is no longer possible to overlook. Also, the use of GHGs is gaining ground internationally as an overall indicator, which makes it convenient when relating to other studies (IAEA 2005). A shortcoming of the indicator however, is that it does not show environmental damage caused by toxins, nor does it valuate loss of biological diversity.

The study considers only wall constructions and their environmental impact during material extraction, production, and transport to building site. Energy use during operation phase is not considered and neither is varying maintenance requirements. When estimating the U-value, the potential effect of heat storage in the materials is not considered. Similarly, a possible gain from CO_2- storage in biomass materials is not included in the calculations. CO_2- storage would certainly give large effects if included, but since there is little consensus on a method of calculation, it is left out. The analysis does not include financial assessments.

The GHGs are calculated for each separate layer of the walls and summarized. The transport distances from production to building site are estimated as average for Norwegian building materials (Berge 2002, p. 9). Data on GHGs for the respective materials are mainly obtained from the Norwegian Building Research Institute.

RESULTS

Wood framework

Wood framework insulated with mineral wool is considered to be the most typical wall construction utilized for single unit dwellings in Norway. Most layers; construction elements as well as outside and inside cladding, consist of wood based materials. Wood as a construction material has long traditions in Norway, and choosing wood for environmental reasons is a relatively new notion. However, the list of reasons is long: Wood is in most places a local material, it is a renewable resource, it is light and versatile, and it can be used for almost all building elements. Designed in the right manner it may last for centuries.

In Wall A (Figure 1), the mineral wool insulation represents by far the largest part of the pie. When mineral wool is replaced with cellulose filament (Wall B), the total amount of GHGs drops considerably. Cellulose filament is made of recycled paper and is a preferred choice

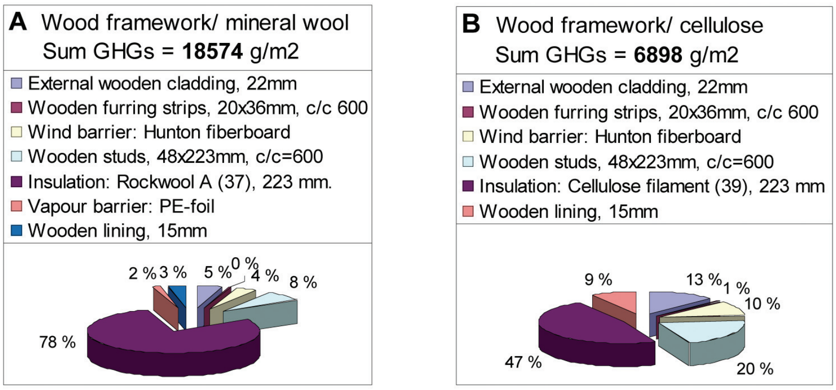


Figure 1: Calculated GHG-emissions for two exterior walls of Wood framework.

for many environmentally concerned home-builders. However, it uses the fire retardant medium of borax which is a harmful toxin (SFT 2006). The environmental load of Wall B may therefore be considerded higher than the GHGs are able to show.

Massive wood

Massive wood has been introduced during the last 20 years as a constructional alternative to concrete. In addition to the general green promotion for wood, keywords are health, fire-safety, and protection against electromagnetic radiation. The Holz 100-concept employs glue-free bonding of grooved boards, and by that good insulation qualities are achieved.

The total impacts of the two massive wood alternatives are roughly equal in size. The GHGs of Wall C (Figure 2) come entirely from wood material. Although wood generally has low emissions during production, the transport generates a considerable amount of CO_2. With a load bearing construction of massive wood and outside insulated wood framework, Wall D is a less expensive and more common construction. The principles of this solution have been employed for the apartment building at Svartlamoen in Trondheim, which has received much attention for its innovative and green qualities. Approx. half of the impact of

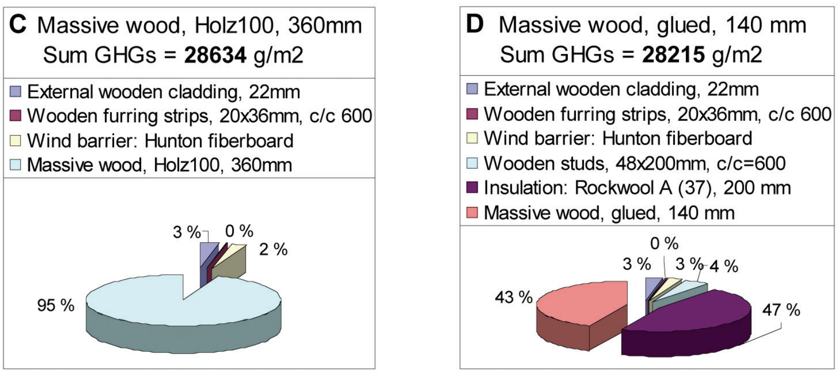


Figure 2: Calculated GHG-emissions for two exterior walls of Massive wood.

Wall D comes from the mineral wool insulation, whereas the impact from the massive wood has been reduced accordingly.

Strawbales

Straw bales are in many rural areas a local waste-product. Inexpensiveness and good insulation properties make it an attractive choice in a growing number of experimental ecological housing projects. It is well suited for self-building, and it is also used in larger scale buildings by progressive architects like e.g. Sarah Wigglesworth in the UK.

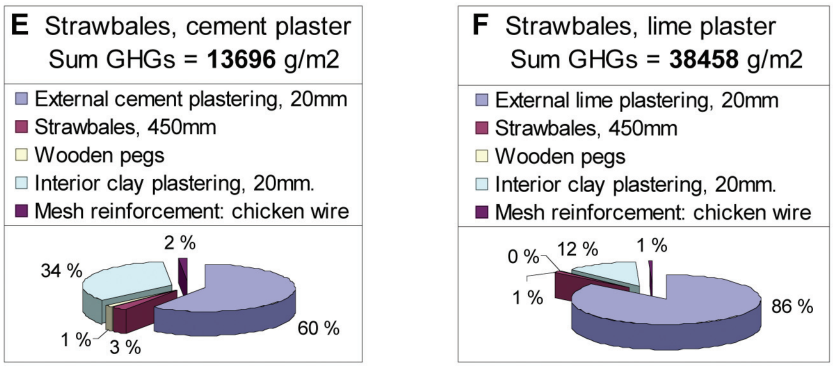


Figure 3: Calculated GHG-emissions for two exterior walls of Strawbales.

The straw itself has negligible impact (1-3% of total), whereas the two layers of plastering contribute to most of the GHGs. Both walls have clay plastering on the interior side. Externally, Wall E (Figure 3) has conventional cement plastering, and Wall F has lime plastering. Lime is considered a technically better alternative to cement because it has a vapor permeability and elasticity better suited for the flexible straw bales. However, the sum of GHGs from lime plastering is considerably higher than from cement because the processing of lime generates high GHG-emissions.

Brickwork

Brick as a building material has long traditions. The burning of clay into constructive bricks requires large amounts of fuels, but the result is strength and high durability. Brickwork can last for centuries and millenniums. Finished bricks are considered clean, and the material has a heat and moisture capacity that can help maintain good indoor air quality. As a small scale architectural building stone it is highly versatile, and depending on mortar type, flexible for numerous generations of buildings.

Wall G (Figure 4) is a cavity wall, where two sidewalls are separated by a drained and insulated cavity. Wall H represents a more common way of utilizing bricks nowadays, as an outside veneer covering an underly-

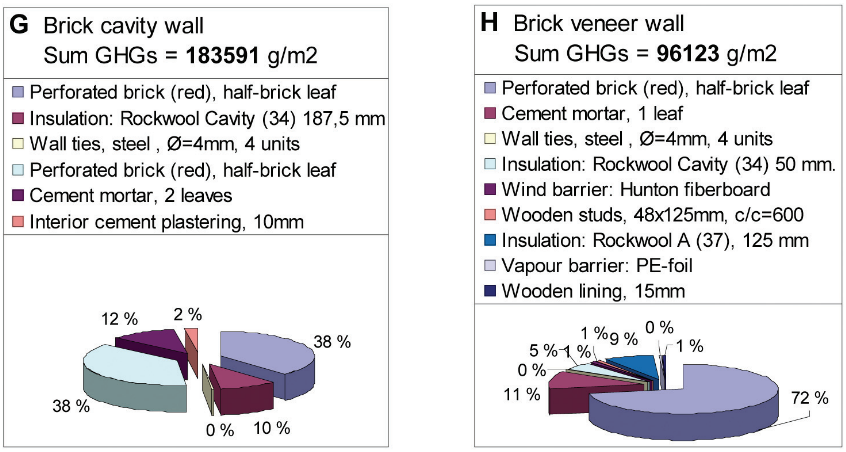


Figure 4: Calculated GHG-emissions for two exterior walls of Brickwork.

ing constructive wall, here in wood framework. The brickwork including mortar accounts for the largest part of the GHG-load in both constructions; 84 % and 83 % respectively.

Aluminium framework

The use of aluminium in constructional parts of a building is relatively new. The extraction from bauxite requires large amounts of energy, and thereby GHG-emissions for first generation aluminium are high. However, aluminium has high durability/ corrosion resistance and high recyclability. An example of an aluminium building interesting in a lifecycle perspective is the Norwegian Løvetann project by Snøhetta/Hydro/Siemens. The suppliers aim at delivering homes with a high environmental profile and individually accommodated design, and the module system is based on an aluminium framework. The façade has a substructure in aluminum and flexible façade panels (www.lovetann.com/no).

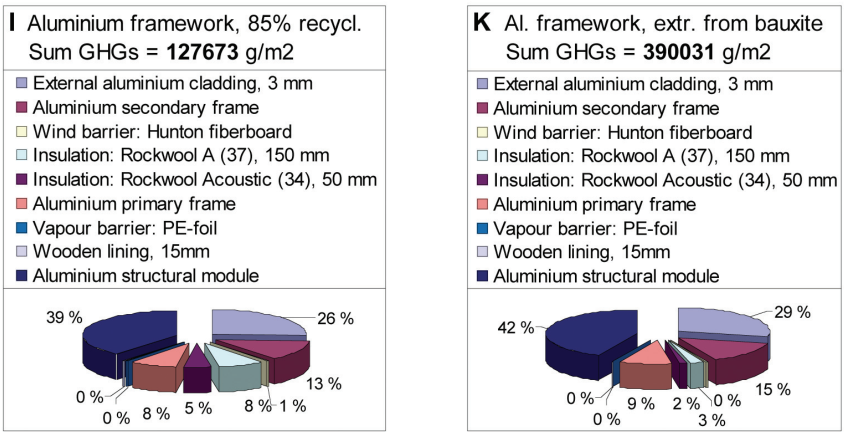


Figure 5: Calculated GHG-emissions for two exterior walls of Aluminium framework.

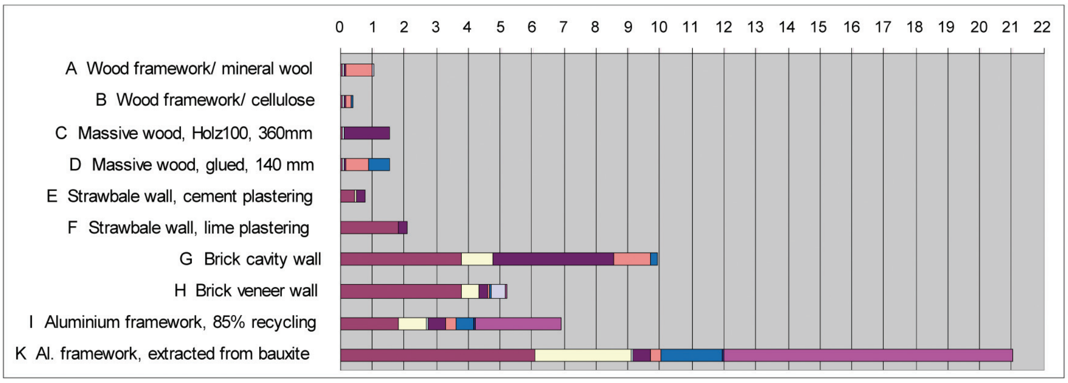
Wall I (Figure 5) is made of recycled aluminium and Wall K employs aluminium extracted from bauxite. There are unanswered questions about how many generations the first load should be allocated to when recycled, and also about what constructive strength recycled aluminium has compared to first generation aluminium. The aluminium parts of the two walls generate approx. 87% and 97% of the total GHGs.

Comparative results

The wood framework/ rockwool construction is, with its environmental impact of 18574 g GHGs per m^2, assumed to have a service life of 50 years. In Figure 6 this is shown as one generation. The resulting impacts of the other wall constructions show how many generations each construction should be expected to last, or their environmentally justifiable lifetime.

Different materials have different potentials at the end of their first generation lives. Wood is highly versatile and has a range of possibilities: Components may be reused, the material may be recycled into fiber boards etc., or heat recovery is achieved when used as fire wood. Masonry is, depending on mortar type, feasible for multiple reuses, although it is more commonly crushed and downcycled into fill material. Metals may also be reused, but they are particularly suitable for recycling through remelting.

Figure 6: Environmentally justifiable lifetime for 10 wall constructions



Discussion

ENVIRONMENTAL JUSTIFIABLE LIFETIME

As the base unit chosen for the analysis, the traditional wood framework appears as a low impact construction. So do massive wood and strawbales. Not surprisingly, the brick walls have higher impacts.

Accordingly we should expect 5-10 generations more for the brick constructions. With the use of lime mortar, this is well obtainable for masonry of good quality. When it comes to the aluminium constructions, we should expect as much as 21 generations for the aluminium extracted from bauxite. This corresponds to a lifetime of 1050 years. One may question if using such a high impact material for the constructive parts of a dwelling is desirable from an environmental viewpoint. Anyhow, design for reuse/ recycling of such a construction is imperative.

The mindset of environmentally justifiable lifetime focuses on DfD for the reason of material salvage, which will in many cases give environmental gain, although not always economical gain within the financial situation of today. However this situation is believed to change, maybe dramatically, over the next decades. Fees on land-fills are rising as laws and regulations controlling the waste streams steadily become stricter. "Few of the principal drivers are yet strong enough to motivate clients and construction teams to implement design for deconstruction. However, their potential influence during the life of buildings now being designed is already apparent." (Addis/ Schouten 2004, p.67) Therefore, an adaptation of the building trade today may pay off also economically in the not too distant future.

Systems for product retrieval and recycling have become mandatory for producers of EE-articles within the EEA area, and are also under implementation for automobile manufacturers. With the quantities of C&D waste in mind, there should be no reason not to consider take-back requirements also for the producers of building materials. More focus on businesses' social responsibility reinforces this trend. Extended producer responsibility (EPR) gives strong incentives to design for extended useful life and maximum recoverable value after use and might radically change the production and delivery of material goods (Addis/Schouten 2004).

ASSESSMENT MATRIX

One can question whether demountable design aimed at material salvage in certain circumstances should be a requirement, in the same way as we have regulations on energy use in buildings. When considering a possible application of demountable design in a new building project, we suggest to take into consideration both the fact that most building types are exposed to increasing turnover rates, however differentiated according to layer stratification, and that different building materials through extraction, production, and transport result in a certain environmental impact. A sketch for a possible assessment matrix is presented in Figure 7. By intersecting turnover rate for the building part in question with its embodied environmental impact, the need for demountable design is visualized. A high score on both axes will demand a strategy of DfD.

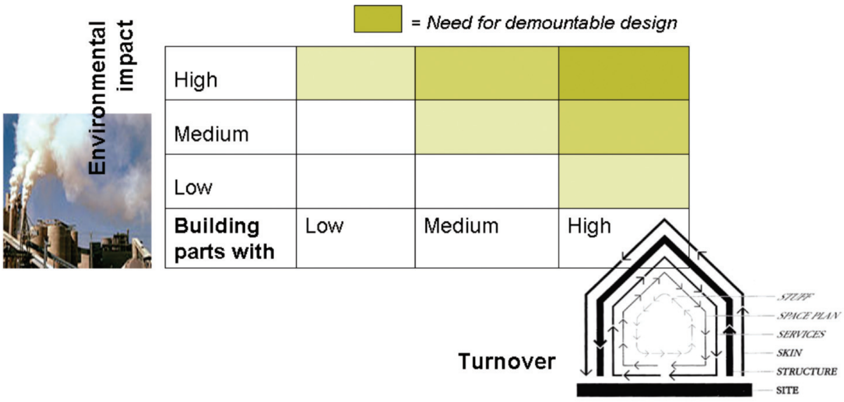


Figure 7: Need for demountable design assessment matrix.

CONCLUSIONS

This analysis supports the idea that the material lifetime and the design of the components ought to be included in the discussion of which building materials are the most beneficial for the environment. High impact materials need to prove their durability, and they need to be designed for multiple lifetimes through a high transformation capacity since a long component lifetime implies a number of potential service lives.

Throughout history, design strategies for facilitating change and flexibility have taken different shapes. The purposes have also varied, principally focusing either on user demands during service life (adaptability and maintainability), or on end-of-life considerations (material salvage) (Fernandez 2003). When designing for end-of-life material salvage, the aim is primarily environmental. By striving to capture the value embodied in the existing building stock, the goal is to suspend the mismatch between building components service life and technical life. Salvaged building materials may reenter the metabolism of the building industry independent of building type and function.

The mindset of environmentally justifiable lifetime focuses on environmental pay-back time and points to DfD specifically for the reason of material salvage. This mode of thinking bypasses economical considerations but aims at environmental benefits through a better material resource management.

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Salvageability of building materials

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Abstract

In the context of reducing environmental impact of constructions by facilitating salvage of building components and materials, the term Design for Disassembly (DfD) is commonly discussed. However, in the different sets of guidelines describing how to design reusable and recyclable buildings, more aspects of the design are stressed. Components should be prepared for all the stages of the salvaging process, including sorting, transport, new design and reassembly. The paper presents a comprehensive systematisation of the DfD principles. The aim is to make up a clear, pedagogic system, as well as to link the design principles to an assessment tool. Also, the system can function as a checklist when designing salvageable materials and components. The paper concludes that since many design aspects are relevant in facilitating the salvaging of building components, the term *design for disassembly* is misleading, and could be replaced by the term *design for salvageability.*

Introduction

DFD GUIDELINE COMPILATIONS

Solutions for environmental challenges in general and for climatic changes in particular are frequently and increasingly debated. The building industry has put much focus on reducing energy demands during user phase of constructions, and a new building code imposing even stricter U-values has recently caused fury among architects and builders in Norway. However, when it comes to greenhouse gas emissions, Norwegian statistics show that a greater part originates in the production of building materials (Byggemiljø 2007). This raises the question of a possible shift of focus to material production, transport, use and considerations in demolishing phase. Since much of the environmental effort that has been invested in the production of building material can be salvaged through reuse and recycling, the demand for salvaged building material is believed to increase in a not too distant future.

Design for Disassembly (DfD) is discussed in a number of studies as a line of action in reducing environmental impact of building constructions. When focusing on durable components and flexible design, several service lives are seen as feasible. With the strategy of DfD there will presumably be less pressure on new material resources and reduced waste, in spite of the increasing turnover of buildings. Several researchers have presented lists of design principles or guidelines for DfD. A brief description of the selected compilations of guidelines is given (chronologically) below:

Bjørn Berge (Berge 2000, p.12-14) describes three principles of *ADISA (assembly for disassembly)*, which are: *separate layers, possibilities for disassembly within each layer, and use of standardized monomaterial components.* The three principles comprise some details in implementation and reasoning.

Scot Fletcher (Fletcher 2001, p.96-99) classifies a total of 37 DfD guidelines into three levels: *systems level* (adaptable buildings which can change to suit changing requirements), *product level* (element manufacture/ construction which allows upgrading, repair and replacement) and *material level* (reuse, recycling and the natural degradation of materials). The *systems* guidelines are further subdivided into four sections under the headings: *design, information, market and disassembly.*

Catarina Thormark (Thormark 2001, p.68) structures 18 design guidelines into three groups: *choice of materials, design of construction and choice of joints and connections.* A separate column in the table gives reasons for the guidelines.

Paola Sassi (Sassi 2002, p.3) focuses on two main areas: 1/ *the process of removal of building elements and materials from building structure* and 2/ *the requirements for reprocessing of building elements and materials to enable reintegration in a new building*. Within these areas the following points are further described: 1/ *information, access, dismantling process, hazards, time,* and 2/ *reprocessing, hazards, durability and information.*

Philip Crowther (Crowther 2003, p.200-201) relates 27 DfD principles to five generative fields of knowledge: *industrial design, architectural technology, buildability, maintenance and research.* Furthermore the principles are connected to the hierarchy of recycling (p.300-301) in a separate table. The reasoning for the selection of principles and for their classification is elaborated in separate sections.

The CIRIA guide by W. Addis and J. Schouten (CIRIA 2004, p.26) synthesizes 19 principles (based on Crowther), and relate these principles to their desired outcome: *component reuse, component manufacture and material recycling.*

The SEDA guide by C. Morgan and F. Stevenson (SEDA 2005, p.23) summarises seven principles for deconstruction detailing. The design implementation and the reasoning are further elaborated in the following sections.

Elma Durmisevic (Durmisevic 2006, p.272-274) lists a total of 37 DfD guidelines, and relate these to three levels (*building, system* and *material* level) within three life cycle coordination scenarios: scenario 1/ *use life cycle < technical life cycle,* scenario 2/ *use life cycle > technical life cycle*, and scenario 3/ *use life cycle = technical life cycle*. A particular focus is set on design configurations that facilitate disassembly.

The classification systems of these lists as well as the level of detail and the number of points vary. Some studies also explain the specific reason(s) for each principle, and link the principles to their desired outcome. However, the overall aim is more or less the same: material resource efficiency through facilitating reuse and recycling.

CHARACTERISATION AND CLASSIFICATION OF PRINCIPLES

The characters of the principles may be divided in three groups:

- Behavioral statements that deal with values and general environmental goals
- Performance standards that are more explicit in their aim and offer specific targets of achievement
- Prescriptive guidelines that offer the designer the most direction in achieving an aim (See Crowther 2003, p.167-168 for further explanation).

All the surveyed lists express, as a behavioral statement, environmental material resource management as the final goal. The lists with few points usually consist of performance standards that are later elaborated in text. The lists with a greater number of points usually consist of prescriptive guidelines that give detailed design information. The characters of the principles are sometimes also mixed within one single list.

The varying classification systems of these lists are keys for understanding their similarities and differences. The guidelines may be classified according to:

- Type of technical benefit such as ease of handling or ease of sorting
- Scale of application such as materials, joints, and overall structure
- Technical level of reuse, such as material recycling, component reuse, and building relocation (See Crowther 2003, p. 297-298 for further explanation).

There are examples of all these classification systems in the surveyed guideline lists. Some of the lists combine two systems so that the principles are related to e.g. both scale of application and technical benefit. Also, some lists give reasons for the guidelines so that the link to their benefit becomes clearer. The question is what the appropriate classification system for an overall systematisation of the DfD guidelines could be.

One may ask if there is a need for yet another list of guidelines. What we do lack however, is a comprehensive system with a consistent and explanatory layout. This system should clarify different levels of scale and be linked with technical benefits (at an intermediate level) as well as with the purpose/ objective of each principle.

FROM GUIDELINES TO ASSESSMENT TOOLS

Some studies present DfD assessment methods as well as lists of design guidelines. A brief description of three methods is given (chronologically) below:

Catarina Thormark (Thormark 2001, p.70) gives an outline of a method for assessment of the *ease of disassembly*. Assessed parameters for the purpose of reuse are: *risks in the working environment, time requirement, tools / equipment, access to joints, and damage to the material caused by disassembly.* As this is an outline for a method only, for the purpose of *material recycling and combustion*, relevant parameters are to be filled in. The possible scores are distributed evenly among the parameters.

Paola Sassi (Sassi 2002, p.4) presents a method for assessment of *suitability for reuse/ recycling/ down-cycling* that is based on more than 60 case studies on building products and construction methods. Parameters are divided into *cost*- and *technically* linked criteria, listed according to the goal for the disassembly. Assessed parameters for the purpose of *general dismantling are: installation systems and fixing methods, access to and handling of building elements, hazards (toxins, structural, handling), time required to dismantle elements, and information required to dismantle elements.* Assessed parameters for the purpose of *reuse as second hand item are: reprocessing requirements to enable reuse, durability, components and subcomponents, hazards, requirements for performance compliance, information required for reinstallation, and fixings required for reinstallation.* Assessed parameter for the purpose of *reuse as new (ADDITIONAL criteria) is: requirements to ensure aesthetic standard.* Finally, the assessed parameters for the purpose of *down-cycling* and *recycling* (assessed separately) are: *reprocessing requirements, durability,* and *hazards*. The technically linked criteria are given a higher weighting and consequently a higher possible score than the cost linked criteria. Except for this, the possible scores are distributed evenly among the criteria.

Elma Durmisevic (Durmisevic 2006, p.203-212) introduces a knowledge model for assessing *Transformation Capacity (TC)* of structures. The method is implemented in case studies on an office building and a facade-system, and in three case-studies of inner wall constructions. The focus is on *disassembly potential* (General dismantling) only, and the model is divided into four levels of abstraction. The two main indicators are *independence* and *exchangeability*. At an intermediate level these are further divided into a *material*, a *technical*, and a *physical level of decomposition.* As sub aspects are listed *functional decomposition, systematization, base elements, life cycle coordination, relational pattern, assembly process, geometry, and connections.* Finally, the input-level consists of 17 determining factors, that each receives an even amount of possible score.

The assessed parameters in all these three tools are classified according to the objective for the disassembly. The objectives refer to the recycling hierarchy, and include:

- General dismantling
- Reuse
- Material recycling
- Combustion

However, there is generally no direct connection between the specific design guidelines and the assessed parameters. Sassi's parameters do correspond more or less to a predefined set of criteria, but these are, however, expressed as performance standards rather than as specific guidelines. This means that the evaluation will be performed at an intermediate level, which may open for a high degree of interpretation.

We would like to investigate if the traceability of the assessment can become more apparent by applying the specific guidelines directly in the method. We therefore suggest the possibility of transforming the overall system for DfD guidelines to an assessment tool. In this way we will achieve a direct link between the guidelines and the assessed parameters.

Suggested Systematisation

MULTI-PURPOSE SYSTEM

The aim of the overall systematisation of the guidelines is threefold: It should make up a clear, pedagogic system suitable for communicating both the basic points and the details of the principles to architects and others involved in the building design process. Secondly, the system should be convertible to an assessment tool to be used when choosing building components for a new design with respect to their potential at the stage of deconstruction. Also, the system could function as a checklist when designing salvageable materials and components.

The design guidelines are classified by combining the three systems of classification previously described (Fig. 1). Since the principles are relevant at different scales of application regarding construction, it is suggested to first arrange them at a *component*-, a *construction*- and an *industry*-level of *scale*. The component- and construction-level focus on building design, while the industry-level focuses on legal and financial aspects that represent constraints for the building industry. In an intermediate section, each level consists of relevant *criteria* that describe the core points of a group of design *strategies*. The criteria are expressed as performance standards, whereas the strategies themselves describe how to achieve these standards. Some criteria are relevant at more than one level. For instance the theme *information* is relevant at all three levels, but addresses different topics. At the component- level; tagging of materials and components, at the construction- level; updated as-built drawings and guidance for deconstruction, and at the industry-level; dissemination of knowledge to designers and builders. The strategies can further be connected to their primary *objectives*, which may be *maintenance, adaptation, building relocation, reuse of components or material recycling*. Through these objectives, salvage of building material will presumably be achieved, which in turn aims at the more general goal of resource efficiency and overall sustainability.

The objective column of the scheme shows that each strategy may have relevance for one or more objectives. Besides the visualization of the relevance of each strategy, a weighting of importance can also be performed. Not all strategies for a criterion are necessarily relevant in each case even though listed in the overall scheme, whereas others may be highly stressed. The result will also depend on goals and priority-setting of the users. Thus, the complementing of the matrix could be subject for a study on its own, and the spaces are therefore left blank at this point.

The next step is the transformation into an assessment tool. The reasoning for the specific principles can help singling out the relevant guidelines for each assessment. In a case study on massive wood construction components (Nordby et al. 2007b), the principles that are relevant for assessing the reusability of whole components are collected and weighted for use in this particular context. The assessment thus represents a pilot study of using the design guidelines directly for an evaluation of building constructions.

PRIORITIZING THEMES

From the surveyed compilations, a set of strategies has been selected. Naturally, some strategies are more basic than others. The strategy *use mechanical not chemical connections* is included in all the surveyed lists in one form or the other. Actually, there are several physical levels where this strategy may apply; when materials are joined together to form a component, when components are joined together to form a building layer or constructional part, and when constructional parts are joined together to form a building. For this reason, the criterion *flexible connections* is relevant at both the component- and construction-level.

It is widely recognized that it should be possible not only to disassemble components and constructions, they should also be prepared for the other stages of the salvaging process, including sorting, transport, new design and reassembly. The remaining criteria at the component- and construction-level of scale reflect these other desired characteristics: A *limited material and component selection* simplifies dismantling and sorting and enables quality control of components before reuse. *Durable design* facilitates dismantling and reassembly, and increases the amount of components suitable for reuse. A *layered construction* will grant structurally independent and exchangeable building parts. *High generality* of components and constructions makes reuse more probable because of the architectural flexibility for a second service life. Finally, *information and access* facilitates the planning of dismantling and the dismantling process, and it also simplifies the sorting and reuse process. Most of these principles are found in the extensive compilation by Crowther, and their general benefits are thoroughly discussed there.

The criteria at the industry level describe the desired characteristics of a construction industry aimed at environmental efficient material resource management (see Sassi 2004). *Life-cycle supportive legislation* is today implemented to varying extents in different European countries, whereas *financial incentives* to support the use and development of flexible designs are probably best known through the IFD-programme of the Netherlands. *Substantiated information* about the benefits of salvageability should be disseminated to designers and builders along with the general knowledge about environmental solutions.

One guideline that is listed in several of the surveyed compilations is the *use of recycled materials*. The reason for this guideline is to support the recycling industry. In our understanding this action is not a strategy directly linked to achieving salvageability, but rather a principle that may be supported by financial incentives. This strategy therefore belongs at the industry level.

Avoiding toxic material is not defined as a separate criterion. The subject is relevant in sustainable construction, but not necessarily for salvageability. It should therefore be considered only if it disturbs the recycling processes, e.g. gives rise to health hazards in the work environment. For the reuse of whole components or relocation it is not necessarily relevant.

As far as production conditions are regarded, prefabrication is not considered a desired means in itself. Prefab building may imply, at least in a country like Norway, long transport distances including fuel emissions both in the building- and recycling processes. Therefore, the suggested guideline *use prefabrication* is omitted as a strategy. Focus is rather set on simple construction methods, small scale and lightweight components that can be manually handled, and the use of common tools. By facilitating local and also do-it-yourself building, local reuse is simultaneously facilitated, and environmentally this is the most beneficial strategy.

One criterion completely left out is *time use*. The time required to dismantle elements is crucial for the economical feasibility, and in the field of industrial design this parameter is usually heavily weighted. However, when discussing salvageability, the question of financial cost is not considered relevant. Focus is on environmental cost, which today is not consistently reflected in the economic system. Therefore, strategies that are purely cost-linked are omitted.

S A L V A G E A B I L I T Y

Anne Sigrid Nordby, 23.04.2007

SCALE	CRITERIA	STRATEGIES	OBJECTIVES: Maintenance	Adaptation	Relocation	Reuse	Recycling
Component	Limited material selection	1. Minimise the number of different types of materials in component, including connections for sub-assemblies					
		2. Plan for using a minimum number of connectors and of different types of connectors between components					
		3. Avoid secondary finishes					
		4. Avoid toxic and hazardous materials					
	Durable design	5. Design durable components that can withstand repeated use and outlast generations of buildings					
		6. Provide adequate tolerances for repeated disassembly and reassembly					
	High generality	7. Aim for standard dimensions and modular design					
		8. Aim for small scale and lightweight components					
		9. Reduce the complexity of components, and plan for using common tools and equipment					
	Flexible connections	10. Use reversible connections for subassemblies					
		11. Plan for using reversible connections between components					
		12. Allow for parallel disassembly of components					
	Information and access	13. Provide identification of material and component types					
		14. Identify and provide access to connection points					
Construction	Limited component selection	15. Minimise the number of components and of different types of components					
		16. Minimise the number of connectors and of different types of connectors					
	Layered construction	17. Design a layered construction with structurally independent systems					
		18. Arrange the layers according to the expected functional and technical life-cycles of the components					
	High generality	19. Aim for modular construction and use a standard structural grid					
		20. Reduce the complexity of constructions, and plan for using common tools and equipment					
	Flexible connections	21. Use mechanical not chemical connections between building parts					
		22. Allow for parallel disassembly					
		23. Design joints to withstand repeated use					
	Information and access	24. Identify and provide access to connection points					
		25. Provide updated as-built drawings, log of materials used and guidance for deconstruction					
Industry	LC-supportive legislation	26. Introduce/ reinforce landfill-tax or -ban which limits/ prohibits the land-filling of salvageable construction and demolition waste					
		27. Introduce/ reinforce construction regulations which address life cycle design					
	Financial incentives	28. Support the use of salvageable materials and constructions					
		29. Support research and development of salvageable designs					
	Substantiated Information	30. Provide dissemination of knowledge to designers and builders of the environmental, social and economic benefits of salvageability					
		31. Provide quantification of economic benefits of salvageability in the life cycle of buildings					

Figure 1: Suggested systematisation of design guidelines for salvageability.

The presented systematization reflects the values and priorities of the authors. However, this list could be expanded to include other criteria and more strategies. The main point is that it can function as an overall scheme that relate the design strategies to *scale* of application, *criteria* at the intermediate level, and to the desired *objectives* according to the recycling hierarchy.

DENOMINATION

Design for Disassembly and Design for Deconstruction are terms commonly applied when the aim is expressed as material resource efficiency through reuse and recycling. However, as this study shows, in the different sets of guidelines describing how to design reusable and recyclable buildings, more aspects of the design are usually stressed. Design aspects also relate to the processes of sorting, transport, new design and reassembly, and therefore the term Design for Disassembly can be perceived as confined and misleading. Our suggested replacement is *Design for Salvageability*. The intention of this expression is to include all lines of actions that contribute to salvage of building materials in one way or the other. Maintenance, adaptation and relocation of buildings are considered as possible objectives for the strategies, as well as component reuse and material recycling. It is, however, possible to tailor a more specific term within the concept of salvageability; e.g. when reuse of whole components is considered a prioritized target, the term would be Design for Reusability.

DISCUSSION

Different lines of action may lead to enhancing the environmental performance of building construction, and Design for salvageability is one of them. The proposed systematisation of guidelines defines criteria that can lead to environmental advantages assuming that there is no suboptimization. The strategies should therefore be checked against other environmental concerns.

The scheme relates the design strategies with:

- Levels addressing *scale* of application
- Operational *criteria* at the intermediate level
- Desired *objectives* according to the recycling hierarchy

When used as an assessment tool, the relevant strategies that relate to the objective of each assessment can be singled out and adequately weighted.

The fact that the same strategy can facilitate different objectives as well as support different overall goals can be confusing. Some of the criteria, like flexible connections, will facilitate all the listed objectives. In addition, flexible connections may be a means to user flexibility which can result in added value of the property. The objectives in the scheme are structured according to the recycling hierarchy, which indicate that some options are more environmentally sound than others. Reuse is considered a better choice than recycling because less processing means less energy spent and less emission released; hence the total environmental burden is less. The highest level in the hierarchy is considered to be maintenance, because frequent care saves the building from deteriorating with a minimum of environmental (as well as financial and practi-cal) effort (Brand 1994).

Whereas the objectives of preparing buildings for adaptation and maintenance are now being performed because these benefits are in demand by clients (Sassi 2004), the objective of preparing buildings for relocation is usually reserved for temporary applications like school pavilions and exhibition spaces. The preparation for recycling and reuse, however, is mainly focusing on environmental gain, and will probably not be extensively performed as long as the financial and legislative constraints are designed to support short-term financial profit rather than sustainability in the life cycle of buildings.

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3.2 Reusability of massive wood components

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Abstract

Massive wood is considered to be an environmentally beneficial building material, however it is not common to design components for a second service life. In a case study, we investigate how the component design influences the reusability. The criteria used are: *limited material selection, durable design, high generality, flexible connections, and access and information.* Five Norwegian massive wood constructions are compared: log construction representing the vernacular tradition, customized massive wood components manufactured by Moelven and Holz 100 representing presently used component types, and the modular massive wood components of Valdres Tremiljø and "Klimablokken" representing innovative designs, the latter still at the prototype stage. The results indicate that there are great potentials to improve the reusability for the most commonly used components types. Improved generality of the components will give architectural flexibility in a second service life, which is crucial to increase the likelihood of reuse.

Introduction

MATERIAL RESOURCE EFFICIENCY

The Norwegian building industry suffers from a poor material resource management. This is reflected, among other factors, through a low percentage of reuse and recycling of building materials. Coupled with high activity, the negative environmental consequences are found in both ends of the material flow, and consist of increased pressure on new raw material as well as of growing landfills with toxic emissions. Also, on the way from cradle to grave, the processing and transport of materials consume large amounts of energy.

A suggested strategy for reducing these negative impacts is to facilitate the use of durable and flexible components that can be used for generations of buildings (Berge 2000). A high environmental input in the production of building materials can be regarded as an investment, and should be reflected in a correspondingly long component lifetime, or environmental payback time (Nordby et al. 2006). Furthermore, seeing that we often get a mismatch between the long technical lifetime of components and the short service life of a building or of a building layer, building components should be prepared for probable alterations. In spite of the fact that building turnover generally is increasing, this strategy would result in greater resource efficiency because the components could enter a number of different building configurations. Important, however, in achieving closed loop material cycles is to design the components and constructions in ways that make salvage not only feasible, but advantageous.

Vernacular building methods are often highlighted as being resource efficient, a characteristic that also may include reusability. Brick buildings from the 1920s and earlier are usually laid with lime mortar, which makes deconstruction feasible. Since bricks are very durable they have commonly been reused in new constructions. Also timber constructions were designed for disassembly and reuse. The traditional Norwegian log construction was prepared for both replacement of units, remodeling, and relocation. Often the house was a part of the luggage when a family moved from the countryside to a nearby town.

However, we have not brought these design principles into the contemporary building industry, and as a result the post-war building stock is not particularly salvageable. It appears as a setback when bricks carefully salvaged from buildings of the 1800s are reused in new walls and laid with cement mortar. The very reason it is feasible to deconstruct the old brick walls is the flexible lime mortar. With the solid cement mortar, one cannot assume that more future lifetimes are obtainable. Paradoxically, along with the development of advanced technology, the intelligence of the building methods that earlier supported flexibility and long life, has vanished.

WOOD AS BUILDING MATERIAL

Wood as a construction material has long traditions in Norway, but the focus on wood as an ecologically preferable material is a relatively new notion. Anyway, the environmental rationale for using wood is manysided: Firstly, wood is a renewable material with fairly low environmental impact in production. Since forestry is a widespread industry, timber is in most places harvested locally, and consequently energy use for transport is moderate. Wood is also highly versatile and can be used for almost all building elements, and designed in the right manner it may last for centuries. Secondly, the contribution of wooden surfaces to a healthy indoor environment is highlighted as an environmental benefit. The capability of storing heat as well as moisture helps balance the air quality. However, to achieve this it is important to avoid impermeable paints and varnishes.

Thirdly, one can argue that wooden components will delay the negative climatic effects through CO_2-storage. All growing biomass material transforms CO_2 from the air to glucose, and it will stay in this chemical bond till the material burns or decomposes. If more biomass material was used in building construction, the effects of the rising CO_2-content in the atmosphere could be moderated. This strategy would give mankind more time to find good solutions to the energy challenges. The argument of CO_2-storage is a point of particular interest regarding the use of massive wood because the material volumes involved in building are greater than in the more common wood framework. Massive wood components have been introduced during the last 20 years as a constructional alternative to concrete, promoted by sustainability issues as well as time efficient construction. Some component types combine structural capacity with good insulation qualities, and thereby it is possible to build complete insulated walls with simplified constructional operations. If parts of the Norwegian building mass were substituted with massive wood, we could achieve considerable reductions of CO_2 .

When it comes to salvageability, wood has a great potential through a set of cascade chains that can extend the material's useful life, e.g. reusing of components, reprocessing into particleboards, pulping to form paper products, and burning for energy recovery. It can be questioned, however, if down-cycling necessarily will lead to environmental benefit. Such procedures most often include transport as well as industrial processes that demand energy and release emissions and waste. The waste hierarchy therefore points to reuse of components as being preferable to recycling and recovery, as the material quality then is retained at a minimal environmental cost (Crowther 2003).

AIM OF RESEARCH

Since the reuse of timber constructions has long traditions in Norway, it seems timely to pursue these traditions in the context of sustainability, and forward them to industrialized building. Although our society may have other reasons for salvaging material than in earlier times and although the economic framework is quite different, the design of the components themselves remains an important parameter. Massive wood as a building material has a great potential of meeting challenges in a low carbon society, but the components generally lack reusability. For these reasons, we focus on *reuse* of *components* in a case study on *massive wood*. We wish to decompose the term reusability, and investigate exactly what factors that make a massive wood component reusable. The case study includes a traditional log construction and compares it with contemporary methods of massive wood. The aim is to investigate how the component design limits or supports the reusability. Since this is a pilot case study, the assessment method is also tested and commented.

Analysis

THE ASSESSMENT METHOD

The principles of salvageability (Nordby et al. 2007a) are converted to an assessment tool (fig.2). The criteria within the component-level of the system are: *limited material selection, durable design, high generality, flexible connections, and information and access*. The reasoning given for the specific strategies helps differentiating their importance for the assessment of massive wood components. We have assumed a relative importance that is shown with a number of x. Furthermore, we have given each strategy a maximum score that reflects relative importance within each criterion A total of 24 points are given to each criterion. These points can be easily distributed amongst the different numbers of strategies as well as amongst their relative importance.

Then each case is given scores for their qualities. The scores are (also) based on judgements made by the authors, and are subject to interpretations. However, a principle followed is that no score is given when desired characteristics are not present, and maximum score is given when the desired characteristics are fully present. In figure 3, combined scores for the different criteria are shown as clustered columns. The total number of points for each case object is not added up, because the criteria are considered to represent different aspects of reusability. These aspects may vary in importance from one assessment to the other.

THE SELECTION OF CASE STUDY OBJECTS

The reusability of five Norwegian massive-wood components is compared: Traditional log construction, customized massive wood components manufactured by Moelven and Holz 100, modular massive wood components manufactured by Valdres Tremiljø, and finally the modular concept “Klimablokken”. Although the manufacturers Moelven and Holz 100 also provide modular components, we have chosen to include only the customized wall elements because those are the most commonly used, and also because that will give the selection of case objects a sufficient variety. Size, shape and connection methods are the most important parameters in separating the case objects. The selection thus represents a diversity of solutions: a vernacular building system, three presently used component types, and one innovative concept still at the prototype level. The functional unit is one typically sized wall component.

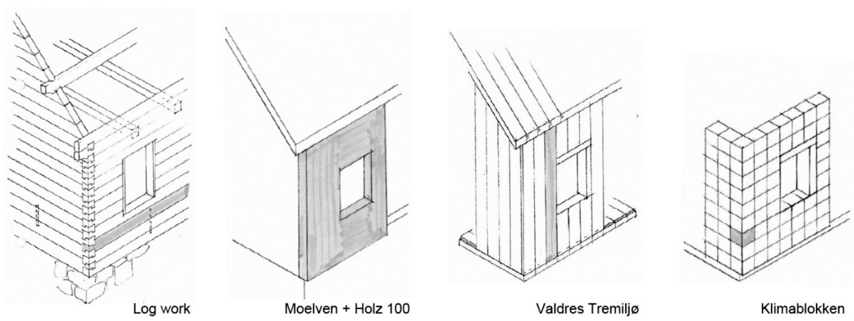

Figure 1: The case study objects, with the functional unit shaded.

R E U S A B I L I T Y OF MASSIVE WOOD COMPONENTS Anne Sigrid Nordby, 22.04.2007

SCALE	CRITERIA	STRATEGIES	REASONING	ASSESSMENT: Relative importance (for criteria)	Max score	Log work	Moelven	Holz 100	Valdres Tre	Klimablokk
Component	Limited material selection	1. Minimise the number of different types of materials in component, including connections for sub-assemblies.	• simplifies dismantling and sorting • simplifies quality-control of components before reuse • makes reuse more attractive due to greater number of fewer material types	xxxxxxx	14	14	10	13	10	13
		2. Plan for using a minimum number of connectors and of different types of connectors between components	• simplifies dismantling and reassembly of components	xxx	6	6	6	6	6	6
		3. Avoid secondary finishes	• reduces potential deterioration of usefulness/ attractiveness for reuse	x	2	2	2	2	2	2
		4. Avoid toxic and hazardous materials	• reduces potential health risks that might otherwise discourage disassembly	x	2	2	2	2	2	2
	Durable design	5. Design durable components that can withstand repeated use and outlast generations of buildings	• reduces damage to components and thereby increases the amount suitable for reuse	xxx	18	18	18	18	18	18
		6. Provide adequate tolerances for repeated disassembly and reassembly	• facilitates dismantling and reassembly	x	6	6	6	6	6	6
	High generality	7. Use standard dimensions and modular design	• gives architectural flexibility in second life	xx	12	9	0	0	12	12
		8. Aim for small scale and lightweight components	• eases handling and transport • facilitates self-building and local reuse • gives architectural flexibility in second life	x	6	4	0	0	4	5
		9. Reduce the complexity of components, and plan for using common tools and equipment	• special tools may not be identified or available • facilitates self-building and local reuse • gives architectural flexibility in second life	x	6	6	0	0	6	5
	Flexible connections	10. Use reversible connections for subassemblies	• enables dismantling of subassemblies • enables quality-control of components before reuse	x	3	3	0	0	3	0
		11. Plan for using reversible connections between components	• enables dismantling and reassembly of components • reduces contamination of materials • reduces damage to components	xxxxx	15	15	15	15	15	15
		12. Allow for parallel disassembly of components	• simplifies dismantling, particularly when only some parts of a building are being removed	xx	6	0	0	0	0	0
	Information and access	13. Provide identification of material and component types	• facilitates the planning of dismantling and the dismantling process • simplifies the sorting and reuse process	x	12	0	0	0	0	0
		14. Identify and provide access to connection points	• facilitates the planning of dismantling and the dismantling process	x	12	6	6	6	6	6

Figure 2: The assessment scheme showing criteria, strategies, reasoning, assumed relative importance (within each criterion) and scores.

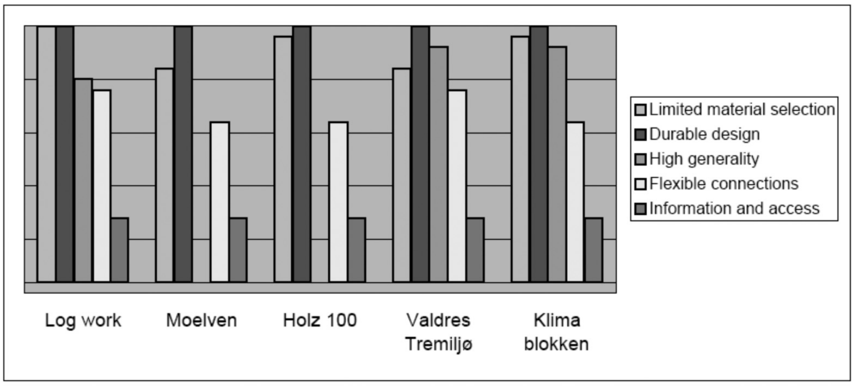

Figure 3: Scores for each criterion, shown as clustered columns.

Discussion of results

LIMITED MATERIAL SELECTION

A limited number of materials is desirable because it simplifies the dismantling and sorting process. Massive wood components are all basically made of wood, but the different connection methods for subassemblies make them different. The log is the only component that consists of wood throughout and that has no connectors, and it therefore receives full score. The other case objects have only one type of connector for the subassemblies; glue for the Moelven component, wooden pegs for the Holz 100 and Klimablokken components, and screws for the component of Valdres Tre. However, the nature of the connectors departs from the basic wood material to varying extents.

When it comes to the need for connectors between components (quantities and types), all the cases are assessed as moderate. Also, a full score is given for avoidance of secondary finishes and of toxic and hazardous materials, although these strategies are not considered highly relevant within this context.

DURABLE DESIGN

All the assessed components are considered to be durable. Although the wood quality may vary, this is not connected with the design of the construction components. High quality wood may last for centuries, even as external cladding if appropriately designed. Since also the tolerances are regarded as adequate, all case study objects receive full score for this criterion.

HIGH GENERALITY

A high generality of building components will give architectural flexibility in a second service life, and this is crucial to increase the likelihood of reuse. Simple and common construction methods, standard dimensions and small to moderately sized components aim at giving freedom of design in a second service life, whereas too large and specialized components can only repeat the same building. The case objects of Moelven and Holz 100 belong to the latter category and demand crane equipment for construction as well as deconstruction. They therefore receive zero points for this criterion.

Vernacular log work is based on modules; the module being a quite imprecise log that requires adjustments for construction and for reuse. Because of this irregularity, traditional log construction does not receive full score for standardization. Industrialized versions of log construction, however, would have received a higher score for this criterion. The scale and weight of the log is assessed as moderate, and full score is given for low complexity and for being workable with common tools.

The Valdres Tre and Klimablokken components receive the best ratings for standard dimensions and modular design. They have both relatively low complexity, and scale and weight is low to moderate. This means that these components can be adapted for pre-fabrication in an industrial plant as well as for self-building. Also, the building can be constructed with common tools, something which is considered to facilitate local reuse. Within the criterion of generality, these two case-objects are therefore assessed to have the highest potential.

FLEXIBLE CONNECTIONS

Reversible connections between components are seen as a prerequisite for dismantling, and this strategy is therefore given the highest score within the criterion. All the components allow for reversible connections, although the component designs do not necessitate specific solutions. When it comes to reversible connections for subassemblies, only the components of Valdres Tre can offer this. Log construction also receives full score for this strategy because there are no subassemblies. However, this aspect is not seen as important for the objective of reuse. None of the components allow for parallel disassembly.

INFORMATION AND ACCESS

It is not common to label information about material and component type directly on wood components. One may claim that this is not necessary, because the wood material speaks for itself. Traditionally, logs were marked to identify where in the wall the component belonged, but this was not connected to material and component type. However, in a possible future where more focus is set on salvageable building materials in industrialized building, this line of action may be developed further. Here the field of product design can serve as a model for the building industry.

Although connection points are not identified, access is more or less evident in the constructions. This is true for all the components, and they therefore receive half score for this strategy.

THE ASSESSMENT METHOD

In this study, we see that both the objective of the assessment *(reuse)* and the function of the case objects *(construction components)* are decisive factors for the weighting of the strategies. The reasoning given is also geared towards the objective of the assessment. If the objective was recycling instead of reuse, other strategies would have been stressed, e.g. *4; Avoid toxic and hazardous materials,* and *10; Use reversible connections for subassemblies.* Likewise, if the function of the case objects happened to be external cladding, e.g. strategy *3; avoid secondary finishes*, would have been considered more relevant than it is for constructions. In this way, the resulting weighting of each assessment will vary.

Furthermore, the criteria are considered to represent different aspects of reusability, and therefore they may also vary in mutual importance from one assessment to the other. More case-studies are needed to further investigate the usefulness of the method.

Besides examining the reusability of massive wood components, we wanted through this study to investigate the use of design guidelines as an assessment tool. The assessed parameters correspond directly with the strategies relevant for reusability of components, and they are expressed as specific design guidelines rather than performance standards. The method was therefore expected to give precision and transparency.

However, there may be a mismatch between the degree of accuracy of the scheme and the more approximate estimate of the qualitatively given scores. This suggests that an assessment method using performance standards at an intermediate level (Sassi 2002) may be just as relevant. On the other hand, this check list concept can be developed further through more case studies. We believe that it is important to retain the principle of traceability.

Conclusions

The results of the assessment show that the case objects differ from each other mainly on two criteria; *limited material selection* and *high generality*. Firstly, different types of connectors differentiate the wood components. Secondly, and most importantly, large differences are found for all the strategies within the criterion of high generality. The results indicate that there is a great potential to improve the reusability for the most commonly used Norwegian massive wood components. In a potential redesign, attention should be paid to the properties that give the components high generality and thereby architectural flexibility in a second service life.

If better reusability of the components was achieved, massive wood could become a first choice building material for closed loop buildings in a low carbon society. Small to medium scale modular components can be manufactured in industrial plants as well as locally by hand. The components should be workable with common tools because this is flexible and will facilitate self-building. In turn, self-building will address local reuse, which is the best environmental option.

When exploring the assessment method we see that transparency is achieved, but that there may be a mismatch between the degree of accuracy of the scheme and the more approximate estimate of the qualitatively given scores. More case-studies are needed to further investigate the usefulness of the method. However, we believe that the direct link between the guidelines and the assessed parameters is a step in the right direction.

To make reuse happen, there are obviously also other parameters than appropriate design that should be considered. Reuse was more commonly performed at earlier times because, among other factors, it was more cost-efficient to invest in work-hours than in material resources. It therefore became cheaper to reuse components than to buy new building material. Today it is the opposite trend, at least in the industrialized part of the world. However, environmental concern is slowly changing the legal and financial framework of the construction industry. Still, adapting the mindset and culture of decision makers is probably the hardest task.

Finally, the strategies for reuse should be seen as a source for architectural potential, not as a limitation. Durable and flexible material components aim at an environmentally justifiable lifetime, and a limited material selection facilitates the dismantling and sorting process. In addition, simplicity in the design may be regarded as an architectural quality: By restricting the material use and by keeping each component simple and clear, the buildings architecture may gain in refinement (Monsen 2006). The lesson is similar to what many architects teach: Keep it simple! Avoid overloads and fussiness, and cultivate each building material at its' own premises.

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3.3 Criteria for salvageability: the reuse of bricks

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4.1
Salvageability, implications for architecture

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Six criteria for facilitating reuse and recycling of building materials are explored in an architectural context. The tectonic approach is used in the discussions, which aim at contributing to a debate on environmental design in general.

Abstract

In the endeavours of reducing environmental impacts of constructions by facilitating salvage of building components and materials, affiliated design strategies have been identified. These strategies inform the design of building components as well as constructions. In this paper, the challenge of turning the strategies into architecture is discussed. The overriding hypothesis is that the demand for salvageability of building materials may be seen as a positive driver for architectural design. The research uses theory from earlier studies, and also points to building examples from past and present. We ask what the design consequences are if the strategies are strictly followed, and in what ways these strategies may coincide with typical professional approaches of creating architecture. Practical consequences are also considered. Through these discussions it is shown that the criteria for salvageability can be linked to the tectonics of buildings, in the sense that environmental logic can substantiate design concepts. The focus shifts from the restrictions that the demand for salvageability may pose upon construction, and rather point to potentials for creating meaningful architecture for a low-carbon society. A process oriented building practice may challenge the prevailing view on architectural design. However, as a key, the building component is emphasized as an operational and responsible base unit.

Introduction

The aim of this article is to couple the findings from the research of salvageability with the field of architecture. Salvageable constructions aim at resource efficiency of materials through facilitating reuse and recycling of components. This article discusses in what ways the criteria for salvageability, as measures for sustainable construction, can be integrated as an innate part of the design process.

Generally, measures for sustainable construction, such as thermal insulation standards and waste reduction requirements, are implemented through regulations in the building code and through financial incentives. These are important policy instruments in gearing the overall building activity towards more sustainable solutions. However, regulations do not principally aim at a change of mind-set, and are more often perceived as obstacles in achieving good design solutions. An important motive for this study is to bring research results closer to practical design work and to the sphere of interest among architects. As there seems to be significant interactions between the theory of salvageability and some basic elements in architectural design, the overriding hypothesis is that the demand for salvageability of building materials may be seen as a positive driver for architectural design. The core questions are related to the architectural consequences of using the design strategies as "rules" for design, and in what ways these strategies may coincide with various professional approaches.

The discussion is structured according to the criteria for salvageability. The study explores in what ways this field of knowledge may influence building practice and architectural expression, and points to building examples from past and present. The examples are chosen because they display design principles discussed in the text, but are not necessarily designed according to the principles of sustainable construction. For the investigation, the tectonic approach is used as an instrument. Historical developments and practical consequences related to the criteria are considered, and possible approaches to the different challenges they raise are suggested.

DESIGN AS REFLECTOR OF CONTEMPORARY THINKING

The last century may be regarded as an experimental period of construction. Whereas earlier architectural epochs and most vernacular traditions are based on reuse of building material, the last century stands out as a period of un-salvageable structures. Laminated constructions, fixed installations and the use of more than 100 000 different building materials are factors that make salvage prohibitive in current building. A focus on waste sorting and strengthening of landfill taxes has facilitated an increase in the percentual recycling of Norwegian construction waste, but very few building components are actually reused in their original form. The problem derives from the existing building mass which basically reflects a linear resource use. A parallel trend is that buildings generally have a higher turnover than earlier, and these two tendencies amplify each other. The paper is based on an understanding that this experiment did not convincingly succeed, because the environmental impacts have been too high. The consequences are found in both ends of the material flow through the building industry, and include pressure on new raw material as well as large amounts of waste.

The way buildings are constructed may reveal a society's philosophy about nature. And certainly, the prevailing designs of the present correspond to shopaholicism, deforestation and hasty oil production. Future archaeologists may conclude that material resources in this period of evolution were seen as a means to satisfy a small elite within one generation only. This contrasts with earlier layers in the dig site of humanity, where resource use to a greater extent was managed by small scale economy, stable demography and/ or informed by religion. Ironically, as the built environment is the most prominent and also the most expensive cultural expression, it is also here that we find the most striking symbols of a devastating resource use.

Meanwhile, in Norway there is a strong public consensus today that the greenhouse gas (GHG) emissions must be reduced. Regarding buildings, regulations aim at minimizing energy demand as well as reducing landfill waste. In addition to this, a cut in GHG-emissions should be reflected in the choice of materials and in building methods that facilitate recycling and reuse. Although architects in general are more open to include environmental considerations in the design of buildings now, it is not commonly debated how these considerations eventually influence architectural expression. However, since design has the potential of conveying society's aspirations, architecture can be seen as a cultural vehicle for the journey towards a low-carbon society.

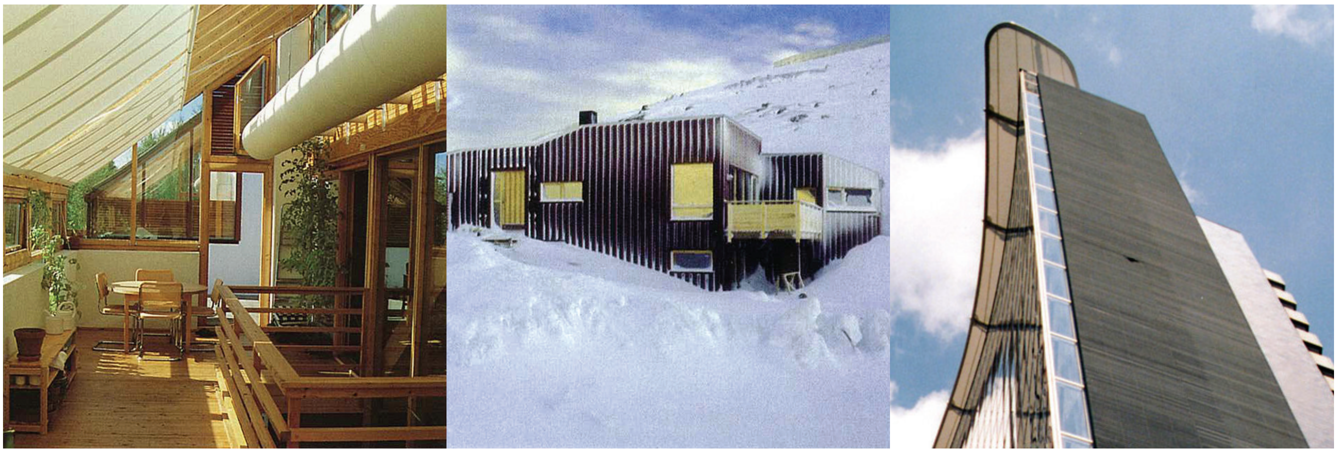
EXPANDING THE CONCEPT OF TECTONICS

In the field of architecture, the term *tectonic* implies using technological parameters as a source for design. The term can be used to describe the design philosophy of load bearing structures, e.g. of how a column head is shaped. A classic Greek column may be seen to have been designed for not only physically being able to transfer the necessary physical loads, but also to visually demonstrate how these loads were brought down from roof to ground. In the modernist building tradition, designing architecture upon the knowledge of the technical properties of building materials and of how the components are most rationally produced has been labeled a tectonic approach. In the Danish book "Tektoniske visioner i arkitektur", Anne Beim defines *tectonic visions* as: "visionary investigations of new materials, technologies, construction principles and building practice as a means to construct (new) meaning in architecture." (Beim 2004 p.6, translated by author). When steel was still a new material, the struggle to develop a suitable architectural language started. Well in line with the economic framework of the industrialism, the modernist style was later described as a rational answer to the conditions for production.

More recent interpretations of the tectonic approach include using measures for local climate adaptations as a source for architectural concepts. These measures may originate from vernacular traditions and may include sun shading devices and the use of thermal storage in building mass. (Beim 2004, p.151-159) This way of defining the term opens for including measures for a responsible resource use in general. Principles for temperature zoning, solar energy harvesting and for natural ventilation may have strong implications for the overall design of a building. We believe that these strategies could also be included in the tectonic tool-box.

Environmental logic is incorporated in the quality and characteristics of different materials, in their extraction and production terms and in their recycling potential. An investigation into this logic may create a knowledge base for achieving the best possible use of resources in a life cycle perspective. Following the tectonic approach, environmental efficiency

Figure 1:
Measures for climate adaptations have strong implications for the overall design of buildings



a) *Norway: Sunroom in passive solar dwelling, Trondheim. Architect: Sintef/ Hestnes 1982. (Photo: F. Østmo)*
b) *Norway: Wind adapted dwelling reduces snow drifts in Hammerfest. Architect: Børve/ Bjørge 1989 (Photo: O. B. Hansen)*
c) *Germany: Wind roof facilitating natural ventilation at GSW Headquarters, Berlin. Architect: Sauerbruch Hutton Architects 1999 (Photo: T. Kleiven)*

may be forwarded into component shape and connection details and subsequently become a premise for construction and deconstruction. Conceptually, environmental logic may inspire the overall design and transform architecture at a larger scale.

THE CRITERIA FOR SALVAGEABILITY

The overriding hypothesis of this study is that the demand for salvageability of buildings may be seen not as just another restriction, but as a positive driver for creating meaningful architecture. The design strategies for salvageability are collected from research in the fields of both building technology and industrial design (Crowther 2003). Based on theories of Design for Disassembly / Deconstruction (DfD) (Berge 2000, Fletcher 2001, Thormark 2001, Sassi 2002, Durmisevic 2006), the selection is further substantiated in earlier studies by the authors (Nordby 2007a). The focus area is resource efficiency of materials through facilitating reuse and recycling of components. This approach is seen as a supplement to resource efficiency through facilitating a long life of whole buildings. As various traditional building practices show, these two concepts are not at odds with each other, but can be pursued in parallel or with varying strength according to the needs and future scenarios of each project.

The strategies are ordered in groups, which are labeled by a set of criteria. The criteria summarizes the core points of the guidelines, and are expressed as general performance standards. We have focused on the principal criteria informing architecture, which are: *Limited Material Selection, Durable Design, High Generality, Flexible Connections, Suitable Layering* and *Accessible Information*. These criteria form the six headings, under which the discussion is ordered. The various reasons for the strategies are described. Also, the various practical and architectural consequences are discussed in the text.

The Architectural Challenge

LIMITED MATERIAL SELECTION

- Minimise the number of types of material, preferably use monomaterial components
- Minimise the number of, and types of, components and connectors
- Avoid toxic and hazardous materials and secondary finishes

A limited material selection is desirable in order to encourage recycling. Simplicity in the material composition for each element, and also for the whole building, gives several advantages in the processes of deconstruction, sorting and reuse. The term monomaterial implies that a component consists of a homogenous material throughout (Berge 2000). Many building products today are laminated and built up of materials with different technical lifetimes. This results in poor resource management because when only one layer wears out, the whole component must be replaced. The use of monomaterials also enables necessary quality-control of components. Another advantage of using fewer material types is that it is possible to sort in fewer fractions when deconstructing the building. This simplifies the sorting job, and in addition it saves space at an often crowded deconstruction site. Furthermore, when the quantity of each material becomes relatively large, the marketing potential after deconstruction becomes more favorable. Toxic and hazardous materials should be avoided as well as secondary finishes because the material then stays clean, both as whole components and as crushed aggregate, and is not subjected to contamination in the form of mixing of material types.

In earlier times, when transport was less widespread and available than today, the industry of construction materials was more decentralized. The local material resources defined the basis for a common building tradition in the region, and this could also give benefits for reuse. In a situation where there are fewer material types to choose from, the market for reuse of materials will correspond more closely to the market for

Figure 2:
A limited material selection facilitates homogenous architecture and design simplicity

***a)** Malta: Local sand stone blending centuries of architecture into the landscape. (Photo: : E. Grytli)*
***b)** Switzerland: Wood unites prefab elements with traditional logs in Versam. Architect: P. Zumthor 1994. (Photo: A. S. Nordby)*
***c)** Norway: Design simplicity of glass and concrete at the Museum of Architecture, Oslo. Architect: S. Fehn 2007. (Photo: A. S. Nordby)*

new products, and reuse may therefore be more easily incorporated into new building activity. However, returning to using only materials from the region may seem an awkward measure today. Building materials for specific purposes, also those solving environmental challenges, may be hard to source locally. A practical approach to this dilemma is to separate bulk material from special components and to make sure that the principal materials to be used are locally extracted. For secondary materials, the environmental cost/ benefits based on freight distance/ material weight contra desired performance in the building should be estimated.

A limited material selection for settlements results in a coherent agglomeration of buildings, independent of styles and time epochs. Thus, different cultural layers are woven together. Also, as seen in Figure 2a, the use of local material types may blend the buidings into their natural surroundings. (For more examples, see e.g. Oliver 2003) A limited material selection also creates a basis for design simplicity, a well-known approach in the modernist tradition. By restricting the material use and avoiding overloads, the building may gain in refinement. Simplicity calls for an investigation of each building material at its' own premises, which may give insights into technical as well as environmental qualities. When this knowledge is put into practice, a sustainable production of building components can take place.

DURABLE DESIGN

- Design durable components that can withstand repeated use and outlast generations of buildings
- Pay attention to joints and connectors, and provide adequate tolerances for repeated disassembly and reassembly

Durable design aims at reducing environmental impact through extending the useful life of materials. In addition to considerate detailing for the purpose of avoiding climatic abrasion etc., a long life of whole buildings may be facilitated through generality and flexibility of the layout. However, in this study the focus is on the component level. Independent of building turnover, durable and flexible components would result in greater resource efficiency because the same components could be used for generations of buildings. According to the theory of environmental justifiable lifetime (Nordby 2006), a high environmental input in the production of building materials should be reflected in a correspondingly long component lifetime, or environmental payback time.

Durability must, however, also be seen in connection with the component's lifecycle and final disposal. Materials with low environmental investments and low risk for pollution do not require a long lifetime in

Figure 3:
Lifecycle design facilitates environmental efficiency by combining the right material quality and detailing with expected functional scenario

a) *Norway: Multi-restorations at the west wing of the archbishop's court, dating back to the 1300s, Trondheim. The use of weak lime mortar in traditional masonry allows for disassembly and modifications so that the functional lifetime of the durable bricks and stone can be extended (Photo: A. S. Nordby)*
b) *China: Cave dwellings, Shaanxi province. The use of local, renewable and bio-degradable building material do not require environmental payback in the same way as high impact materials (Photo: A. S. Nordby)*
c) *Germany: Expo pavilion of paper-tubes and cardboard, designed for short lifetime and easy recycling, Hanover. Architect: S. Ban 2003 (Photo: Hiroyuki Hirai)*

the same way as high impact materials. For short-term building purposes, choosing materials that decay locally without contaminating soil or air might be an overall beneficial approach. By combining the right material quality and detailing with expected functional scenario, salvage of building material becomes differentiated and gives opportunities for resource management that takes the original environmental investment into account.

Architectural quality can be incorporated at both the building level and when designing components, and may in its own right be a facilitator for long functional lifetimes. Therefore, in general, more architectural effort could be spent on building components. However, there are many opinions about what is good design. Surely, some people will passionately salvage what others carelessly throw away. The challenge of the designing architect is to both reflect contemporary spirit and at the same time to give buildings and building components classic qualities that can provide for long lasting relationships with the users. Clever design and careful detailing might increase the affection value. Thus, the chances are great that both the whole building and the components themselves will be maintained and reused by the owners so that an environmentally responsible resource use is achieved.

HIGH GENERALITY

- Use standard dimensions, modular constructions and a standard structural grid
- Aim for small scale and lightweight components
- Reduce the complexity of components and constructions, and plan for using common tools and equipment

Generality is a term that may be used for characterizing both components and whole buildings. A building that has a high degree of generality has the potential for changing its functionality within existing floor plans and deck-to-ceiling heights. A high generality of building components, on the other hand, will give architectural flexibility also in a second service life. This property is crucial to increasing the likelihood of component reuse. Simple and common construction methods, standard dimensions and small to moderately sized components aim at giving freedom of design and will enable use in different architectural contexts regarding functions, structure, expression and detailing, whereas large and specialized components can only repeat the same building. Furthermore, small scale and lightweight components and the use of simple tools and methods will facilitate do-it-yourself building, which is assumed to also encourage local reuse. Facilitating reuse in the private market as well as through the industry increases flexibility of production.
Reuse of building materials is actualized by two approaches, in which the need for generality differs. Firstly, reuse may be based upon purely

Figure 4:
Building components with high generality are architecturally flexible, and can be used in different building contexts

a) *Italy: Marble columns of the antiquity were standardized, however handcrafted and thereby subject to variations in finish. The "spoliated style" forwarded reuse of components, often plundering from conquered land. Saint Mark's Basilica, Venice. (Photo: A. S. Nordby)*
b) *Spain: Bricks are small, "molecular" building units, and flexible for a variety of structural uses and architectural expressions. Vault in the Crypt of the Colonia Güell, Catalonia. Arch: A. Gaudi 1898 1898. (Photo Will Pryce, (c) Thames & Hudson Ltd., London. From 'Brick: A World History' by James W. P. Campbell, Thames & Hudson, 2003)*
c) *Norway: Valdres Tremiljø´s versatile massive wood components are used for walls, roofs and decks in mountain cabins. Architect: M. Øvergaard 2006 (Photo by the architect)*

economic reasons. When it is more expensive to manufacture and transport new materials, salvage becomes an obvious choice. In the second approach, historic building components may be appreciated for their materiality and for their ability for cultural storytelling. In late antiquity and medieval times, reuse or "spolia" was even performed on a political basis as the use of plundered art treasures and valuable building components signalled command over conquered land. Today, reuse may have another value based effect in the context of "compost-modernism" (term introduced by Helen&Hard Architects in the journal Byggekunst 2006/04), namely to demonstrate environmental concern. In salvage on an economic basis, generality is needed because it gives architectural flexibility and because it betters the chances for reclaimed material to match common standards and practices. Historically interesting components, on the other hand, are highlighted independent of their generality, and the remaining material use is seen more as a backdrop. In the latter approach, generality of components will therefore be less crucial.

Variation in the built environment is a human need. When the words *standardization* and *modularity* are used, it echoes the industrial demands of the 1950s and 60s which ran the risk of producing architecture of monotony and tediousness. However, variation can be enabled in different ways. Vernacular building materials are often based on generality, although the handicraft processes tailor the components according to specific needs and according to specific material qualities. This customization may have environmental benefits as e.g. the varying properties of the wood material in each log can be utilized in a best possible way. Also, handcrafted materials give variations in texture that may add to architectural richness. Certainly, preserving historic buildings while maintaining traditional handcrafting skills contribute to a resource efficient material use. However, if reuse of building material is to be achieved at large scale, it must also be facilitated in the context of industrialized production.

If the possibilities for creating a rich architectural language and at the same time the criteria for salvageability are to be met, the scale of the component is of primary concern. Small components, e.g. bricks, are able to generate responses to various formal situations, whereas larger components to a greater extent will "take control" of the architecture. An example of the latter is typical prefabricated concrete wall elements whose sizes and proportions dominate the visual appearance of a façade. Therefore, the two first strategies of this criterion should be read and pursued together. Following a tectonic approach, the criteria for salvageability may become a basis for design at the "molecular" level of construction.

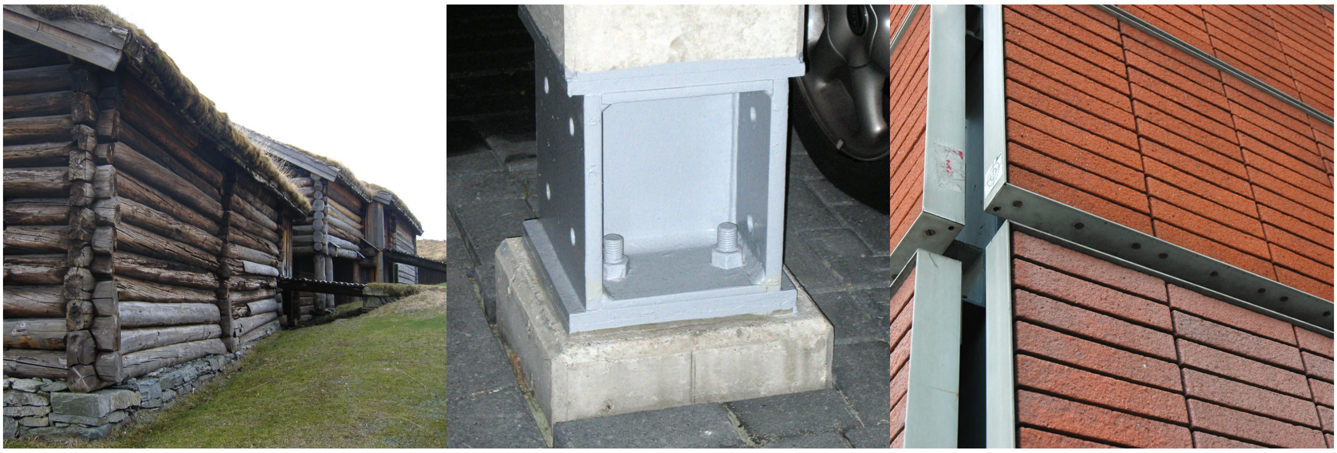
FLEXIBLE CONNECTIONS

- Use reversible connections for subassemblies, between components and between building parts
- Allow for parallel disassembly and reassembly

Reversible connections are seen as a prerequisite for dismantling. Mechanical fasteners like screws and bolts are preferred to chemical bonding of glues and strong mortars, because they will enable deconstruction without damaging the components. Again, vernacular building types present a variety of solutions like transportable tent structures, lumber joint locks and masonry with weak mortars. In modern architecture, flexible connections are primarily developed for short-term uses like expo-pavilions and temporary barracks.

Connection methods may be designed as integral parts of the components' structure and appearance. As is the case when pursuing other criteria of salvageability like durability and generality, a study of connection methods may lead to a deeper understanding of tectonics. Joints are often refined sections of the architecture in both vernacular and modern designs, expressing transfer of loads not only physically but also in a figurative sense. The joining of components can follow different tectonic principles like weaving, stacking and interlocking, and

Figure 5:
Reversible connections can take a variety of shapes, and joints are often refined sections of the architecture in both vernacular and modern designs.



a) *Norway: Traditional log houses have highly flexible joints that allow for exchanging single components, remodeling and relocating whole buildings. Sverresborg open-air museum, Trondheim (Photo: A. S. Nordby)*
b) *The Netherlands: Steel segment connecting concrete column to foundation in the XX office-building, designed for a service life of 20-years, Delft. Architect: J. Post 1992. (Photo: A. S. Nordby)*
c) *France: Demountable system of aluminium frames and bolted bricks also defines the façade expression of the IRCAM-building, Paris. Architect: R. Piano 1988. (Photo: J. Siem)*

these principles also determine the premises for a possible patterned ornamentation of the surfaces.

This component-bound ornamentation is related to the logic of the component, and subsequently differs from the *free* ornamentation that is added to the building independent of the technological context (Selmer 2003). The latter approach includes the use of surface treatments and signs, and may result in a more superficial architectural language. The free ornamentation is more easily influenced by short-lived fashions, and may in the end reduce architecture to mere scenography. If, on the other hand, the aesthetic expression is rooted in the patterns that are determined by the joints' detailing, a tectonic relation between the tactile material qualities and the outward architectural expression is enabled.

A challenge, however, in the broader environmental context regards the carbon footprint of the materials used when the connectors are included. As seen in some newer projects pursuing demountability, such as the IRCAM-building in Paris, a high amount of resource intensive materials like steel and aluminum is used to construct the walls. Although the total environmental load is not calculated here, there is reason to believe that the support system including connectors count for a higher environmental investment than for the primary construction materials themselves. Since salvageability is only one aspect of environmental building measures, there will always be the risk of sub-optimization when working on solving one problem and unconsciously creating others on the way. A holistic perspective must therefore be regarded as a prerequisite in environmental design.

SUITABLE LAYERING

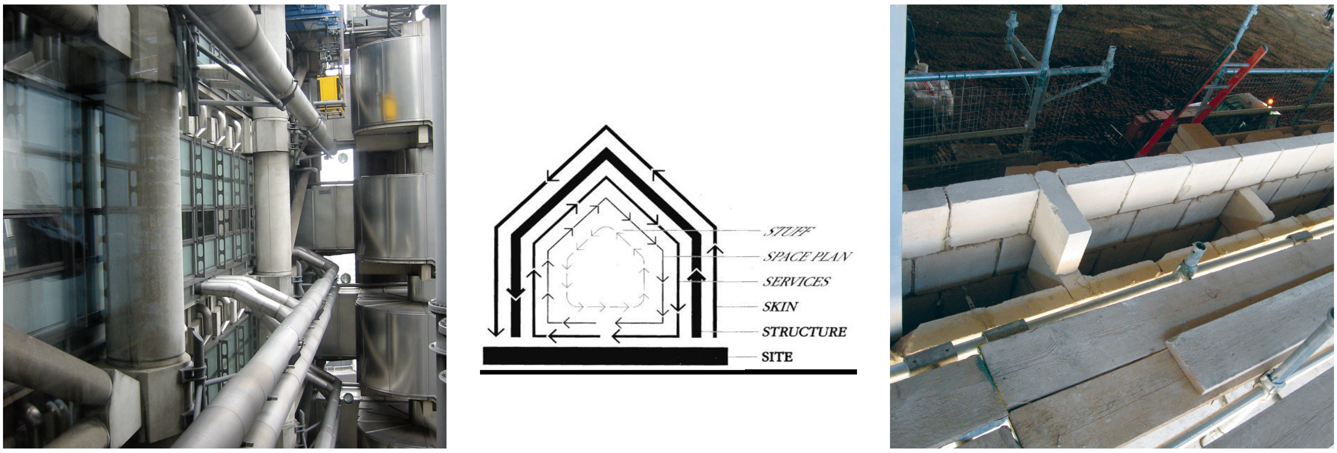
- Design the layers of the construction as structurally independent systems
- Arrange the layers according to the expected functional and technical life-cycles of the components

A frequently recommended principle in life cycle planning is the need for layered constructions. The theory is based upon the observation that different parts or layers of a building are changed at different time rates (figure 6b). Therefore, an adaptive building should allow slippage between differently paced systems. When each layer is made structurally independent and each component is exchangeable, the challenges of mismatch between the often long technical lifetime of components and the often short service life of a building or of a building layer are met. These layers should, moreover, be arranged according to the expected functional and technical lifecycles of the components so that the components which are likely to be replaced first are provided access (Durmisevic 2006). This will reduce damage to components when only some parts of a building are being replaced or removed.

The multi-layered wall mirrors the philosophy of industrialism; to increase the efficiency of the production process through a division of labour (Selmer 2003). One layer is for load-bearing, one for insulation, one as vapour barrier etc. This strategy has evident benefits in creating "intelligent" buildings, where advanced façade structures and HVAC systems capable of regulating climatic conditions aim at lower energy use as well as at increased indoor comfort. Benefits are also gained for maintenance and remodelling when the construction is designed so that each component is individually accessible and exchangeable.

Historically, there is a tendency that the exterior walls of buildings have developed from being integrated, where all functions are attended in one layer, to differentiated, where separate layers serve different purposes. A contemporary exterior wall generally consists of a number of component types that meet different constructional and climate regulation demands. Also, a need for increasing energy performance has involved the use of thicker layers of insulation. These improvements have, however, resulted in more complex and material consuming constructions. On its way towards optimization, the exterior wall may become an arduous engineering task as a number of joining details are to be worked out both structurally and aesthetically. The situation results in vulnerability because there are many locations where the per-

Figure 6:
The two approaches of differentiated and integrated constructions have different consequences for salvageability as well as for design.



a) *UK: Functionally differentiated exterior wall of the high-tech icon Lloyds, London. Architect: R. Rogers 1989. (Photo: A. S. Nordby)*
b) *Principal diagram of time related building layers (S. Brand 1994)*
c) *UK: Functionally integrated hemp/ lime construction in low-tech warehouse for Adnams Brewery, Suffolk. Architect: A. Fitzroy Robinson 2006. (Photo: N. Magdani)*

formance might fail, caused by flaws either in design or in craftsmanship.

Whereas most other criteria for salvageability point to simplifications of building practices, the principle of building layers supports increased complexity. In the perspective of maintenance and remodelling this principle definitely represents an important measure. On the other hand; for the purpose of facilitating reuse after terminated functional lifetime, limited material selection and simplicity of construction methods may be seen as equally important strategies. Components that can meet a number of challenges of the exterior skin may therefore be preferred to specialized components that can carry out only one task. Examples of this difference is shown in Figure 6; pictures a and c.

As a result of these discussions, we have rewritten the heading criterion from earlier studies. Instead of *Layered Construction* we now propose *Suitable Layering*. This stresses the point that in achieving salvageability, a layered construction may not be a goal in itself. However, if the construction is layered, the layers should be structurally independent and also preferably organized in correct order regarding expected lifetime.

The two approaches have different consequences for design. Both imply a focus on the building units and their connections, but in different ways. The layered, functionally differentiated construction tends to define the units as mechanical parts with many detailing opportunities, but also challenges. Here, only the exterior layer is architecturally communicative, which offers a framework suitable for free ornamentation. In the functionally integrated construction, on the other hand, the structure and joints of the units may offer a tectonic detailing that can communicate constructional coherence and contribute to a component-bound ornamentation.

ACCESSIBLE INFORMATION

- Provide identification of material and component types
- Provide updated as-built drawings, log of materials used and guidance for deconstruction
- Identify and provide access to connection points

This criterion is recognized as an important measure in industrial design. In the manufacture of e.g. cars and electronic devices, recycling has been implemented with great rigour. In facilitating reuse, it is an advantage to have product information tagged or printed directly on the components so that material types and qualities are easily separated and sorted after their first service life. Valuable information about the components may in this way be directly forwarded to coming generations and become a basis of assessment for possible further use. Product information may indicate raw material types and qualities as well as company name, production site and year. Other sources of building information like e.g. "as built"-drawings, material-logs and guidance for deconstruction are also of great value for future users and should be updated in connection with renovations. Furthermore, access to connection points should be clearly identified.

There are different practices regarding tagging depending on material type. The Romans started the tradition of making stamped bricks indicating production site or brick-maker, a measure that has made it more interesting for archaeologists to investigate dig sites. More contemporary examples from manufacturing cars and electronic devices include imprints on metal and plastic parts. For storing detailed information that may also be updated later, bar-coded identification or electronic identification chips may be used. However, these methods depend on the existence of similar equipment for future reading (Addis/ Schouten 2004). Therefore, direct tagging is seen as a more robust measure.

In addition to purely technical advantages, tagging of information also has the potential to create decorative effects. Components may be designed so that the surfaces containing information give added value of texture/ relief that may contribute to distinctive architectural expression. Symbols can be standardized so that a simple code language suitable for building components can be developed. Codes and brand-images

Figure 7:
Useful information regarding salvageability can be carried along with the components as well as along with the architectural language

a) *Norway: Carved marks on traditional log construction defines the placement of each log in the system. (Photo: A. S. Nordby)*
b) *Hungary: Old, reclaimed stamped bricks are popular as decorative reuse-objects. (http://forum.index.hu)*
c) *Denmark: The readability of the architectural language gives access to information about material components and their reuse potentials. Half-timbered house in Holbæk. (Photo: F. Hakonsen)*

may in this way give future users and demolition contractors a glimpse of the construction methods and philosophy at production time, as well as the necessary information for reuse.

At the building level, the architectural language may also function as a conveyor of useful information regarding salvageability. This more tacit knowledge is related to the readability of constructions, and is often seen in vernacular traditions. Simple construction methods, integrated functionality of components and the use of monomaterials facilitate this readability. Some building traditions of the past, like the half-timbered house, exhibit the materials as if they were on display. Information about the reuse potentials of the components is thereby made highly accessible to the users of the buildings.

The architecture of the component

Current production of architecture has two serious, and related, pitfalls: On one hand; rapidly changing fashions may turn architecture into mere sceneography, and on the other hand; the demand for high performance may turn buildings into technological challenges that only engineers can solve. Architects tend to work more and more with purely aesthetical questions, leaving the technical considerations to consultants. Possible design influences of technical issues are thereby marginalized.

Lifecycle design may challenge the prevailing view on architecture. Popularly pursued as original and artistic expressions influenced by changing fashions, the dominant contemporary approaches to architectural design are actually reminiscences from the Modern movement. In the 1920s and 30s, the demand of contemporariness was manifested, and also the demand of originality. Although criticisms of the modernist style have been addressed over the past decades, the attitudes that followed with it remain rather unquestioned (Hvattum 2006). Recurringly new design ideas are materialized at a large scale, whereas building components subordinate under the dominating visual appearance. However, these characteristics do not fit well with the criteria for salvageability. On the contrary, process-oriented building practices challenge the view of buildings as art objects. The prototypes for flexible design are rather available in vernacular traditions, and consist of building *patterns*. Here, the cultural framework and physical properties of the materials inform architecture. As earlier pointed out, the criteria of salvageability are often included in this vernacular logic. Steward Brand (Brand 1994), theorist and advocate for lifecycle design, recommends starting out by building in a conservative manner, respectful of regional traditions and the existing urban fabric. During use, each building's uniqueness will come into being.

Physical properties inherent in building components can meet various technical needs. Besides structural strength, weather tightening and thermal insulation, challenges are related to facilitating a healthy indoor environment. Building units may be used as active and operational members of interiors. The ability of heavy materials to store heat can reduce daily heat fluctuations, and sometimes also reduce energy use for heating or cooling. Porous materials with the capacity to regulate humidity may reduce the importance of HVAC installations. Furthermore, acoustic control is managed by building components whose surfaces modify or absorb noise. These measures are integrated with the architecture, and the logic is based on a holistic approach. Although high-tech installations may improve building performance, they may also add complexity and vulnerability to constructions. A focus on the physical and chemical potentials embedded in materials can instead result in more robust solutions. Also, as seen in figure 8, this focus may provide a potential for tectonic relationships.

Leaving the question of whether or not "green" architecture should manifest itself in a certain style, the tectonic approach may be conceived as a more practical concept. Viewing the component as a merger of technological and aesthetical challenges, the tectonic approach acknowledges the logic of the materials as a premise for architectural design.

Figure 8:
Physical properties of building components can meet constructional and environmental challenges, and at the same time substantiate tectonic relationships.

a) *Norway: Acoustic regulation in the grand foyer is facilitated by the use of panelling in oak that also add texture. Opera House, Oslo. Architect: Snøhetta. (Photo: A. S. Nordby)*
b) *Norway: Moisture resistance and moisture capacity of bricks with different surface treatments are combined in a bathroom in Bærum. Architect: K. Hjeltnes. (Photo: A. S. Nordby)*
c) *UK: Cloth cladding designed for a possible short-term life, and a more durable exterior skin of sand/ lime/ cement-bags are used in a combined office/ dwelling intended to change over time, London. Architect: S. Wigglesworth. (Photo: E. Wenn)*

Technical properties like material quality, component shape and connection details may become informative for construction and may inspire a transformation of architecture at a larger scale. As this study tries to argue, environmental considerations should be an integral part of this logic.

The different issues regarding sustainable building practice have various influences on design (see e.g. Larsen et al. 2006). Since the environmental impacts associated with the manufacturing processes cannot be made visible in the finished components, the energy- or CO_2 -content of materials, or their pollution profile can not be linked to architectural expression in the same way as measures for climate adaption and energy harvest. The issue of salvageability, however, has strong implications for architectural design, and the criteria are to varying degrees related to tectonic thinking. A salvageable component design is based on environmental logic at a "molecular" level, and underpins the importance of operational qualities of components. When this usefulness is brought forward and expressed in the aesthetics of a building, it may contribute to give meaning in architecture.

Conclusions

The discussions generally support the overriding hypothesis that the demand for salvageability of building materials provides a potential for architectural design. The findings are, however, varying in substance and in strength for the different criteria. The design strategies with the greatest consequences for the building's tectonics were mainly found within the criteria; *limited material selection, flexible connections* and *accessible information*.

An additional finding is that historical construction methods usually are good examples of salvageable design. This is not only due to *reversible connections*, but for all the criteria regarding salvageability. This leads to the reflection that the investigation of design guidelines for salvageability may be seen as a way of mapping tacit knowledge embedded in traditional building methods. Resource optimization is often an implicit quality of vernacular architecture, but this knowledge is not often explicitly forwarded. The criteria for salvageability may thereby describe and substantiate vernacular logic.

The tectonic approach was found to be useful in the context of salvageability, and in exploring the implications for architecture. Tectonic visions may help bridging the gap between conventional architectural theory and the evident contemporary need to manifest sustainable thinking in the construction of buildings. Thoughtful and up-to-date architecture representing a culture aiming for a low carbon society is operational and responsible as well as sensuously inspiring. Starting with ingenious building units, the architecture is in the details!

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findings and reflections 5.0

This chapter presents the findings, and supplies with reflections on aims, methods and on the significance of the research carried out. In the first sub-chapter, the outcomes related to the overriding scope are presented as well as key findings of the three areas of inquiry. The issue of theoretical contributions is also discussed. The following sub-chapters treat the findings and reflections of the specific research questions asked, structured according to "why", "how" and "so what". The last sub-chapter gives recommendations for future research.

5.1 Main conclusions

OVERRIDING SCOPE

The overriding scope was twofold:

- To investigate building methods that facilitate reuse and at the same time contribute to solving a set of environmental challenges in a long-term perspective
- To explore ways to expand the applicability for salvageability and to transfer the concept to contemporary architectural practice

The first main conclusion is that the challenge of salvageable building methods cannot be solved in one line of action, and that sub-optimizations must be avoided. As pointed out in 3.1 "Salvageability of building materials", the design guidelines reflect also other phases than disassembly in the reuse process, such as sorting, transport, new design and reassembly. Although a transition to demountable constructions is a basic step, all measures are important in assuring resource efficiency in a long-term perspective. This finding resulted in suggesting a replacement for *Design for Disassembly* as a collective term, namely *Salvageability.* Furthermore, since salvageability is only one of many environmental building measures, the strategies for salvageability must be combined with other environmental goals. As substantiated in 3.3 "Criteria for salvageability: the reuse of bricks" and 4.1 "Salvageability; implications for architecture", sub-optimizations may occur when trying to pursue a problem with a limited set of criteria. Therefore, holistic and long-term analyses are needed. This also regards the financial framework of construction practice. In order to make sustainable solutions not only environmentally but also economically viable, the lifecycle perspective must become compulsory in the design of buildings.

The second main conclusion is that for the purpose of expanding the applicability and current interest in salvageability, measures to simplify and operationalize the concept are needed. Such measures are developed throughout the thesis. As shown in 2.1 "Lifetime and demountability of building materials", the rationale for salvageability can be expanded by pointing to the environmental impact of materials as a normative point of departure, and the concept of *environmentally justifi-*

able lifetime assists in strengthening this argument. This rationale can be a supplement to the more acknowledged rationale regarding turnover frequency. In 3.1 "Salvageability of building materials", the design principles of salvageability are operationalized. The structuring of the guidelines and in particular the division into criteria and strategies may assist in making the principles of salvageability easier to understand, and also more applicable for design work and for assessments. 4.1 "Salvageability; implications for architecture" discusses the architectural implications of the guidelines, and aim at a motivation for architects to realize the measures in contemporary building tasks.

KEY FINDINGS

The thesis substantiates that there is a normative relationship between building materials' embodied environmental load and their expected functional lifetime, and thus their need for salvageability. The environmentally justifiable lifetime was calculated for 10 exterior walls, and the graphic visualization clearly shows that - according to this rationale - we should expect high degrees of salvageability for constructions in brick and in aluminum compared to the constructions in wood framework, massive wood and strawbales. The calculation method that was used represents a quantifiable measure for expected building generations.

The principal systematization of design guidelines that was developed in the thesis can be used as a base of information in various types of investigations. Also, it is convertible to an assessment tool. The criteria level is an independent contribution that is significant in a pedagogical context because it summarizes and expresses the core points of the guidelines as general performance standards. The assessment tool and the criteria were used in two case-studies. The first investigated massive wood components and the second investigated brickwork constructions. In both the assessments, historical construction methods showed very good results. The study on massive wood components suggested that there are great potentials to improve the reusability for the contemporarily used massive wood component types by improving their generality. The study of brickwork showed that traditional bricks possess an ideal generality, but that the different ways to achieve flexible connections pose dilemmas. For the purpose of avoiding sub-optimizations in achieving overall environmental goals, further development of lime mortars is recommended as the most promising measure.

The case-studies also explored the assessment tool. The assessment matrix was found to be a flexible system adaptable to various studies, and the method gave a reasonable level of transparency. In an ideal situation, however, a multidisciplinary team of professionals should perform the assessments to guarantee more robust results. In this context, the method was useful in demonstrating historic developments of components and constructions, as well as showing potentials for future improvements. For both the case-studies and the exploration of architectural consequences, the criteria level was found to be useful for structuring discussions.

In exploring the architectural consequences of the design strategies, positive drivers for architectural design were primarily pointed out within the criteria Limited Material Selection, Flexible Connections and Accessible Information. A limited material selection substantiates a homogenous architectural expression, and may also create a basis for design simplicity. Flexible connections can be detailed as refined sections of the architecture, and the joining principles can support component-bound ornamentations of the surfaces. Accessible information communicated directly by tagging or moulding has the potential to add texture/ relief that contributes to distinctive architectural expressions. Also, at the building level, the architectural language may convey useful tacit knowledge related to the readability of the constructions. Generally, the tectonic approach was found to be useful in discussing the architectural consequences of salvageability. Tectonics bypasses the question of architectural style and can therefore contribute to manifesting sustainable thinking at the "molecular" level of constructions.

THEORETICAL CONTRIBUTIONS

Research in the field of DfD of buildings has primarily been oriented towards practical knowledge. Apart from a few exceptions, not much of the literature used in this thesis represents scientific *theories* in the sense that it gives generalized descriptions and explanations. The investigations are explorative in nature and make no attempts at deductive theory-testing. Consequently, most of the findings in this thesis are not to be viewed as contributions to a theoretical discourse, but rather as contributions to expanding existing knowledge.

However, the investigations attempt at developing knowledge that can make the descriptions and explanations more general. Thus, the research may contribute to inductive processes of establishing some new theoretical grounds. One such attempt is demonstrated in figure 5.1.2, which summarizes the ideas presented in 2.1 "Lifetime and demountability of building materials" about coupling environmentally justifiable lifetime with expected turnover as a rationale for salvageability. A second attempt is the systematization of design guidelines presented in 3.1 "Salvageability of building materials". Here, the strategies for salvageability are transformed to a more generalized concept with greater degree of detailing. Also, the use of this systematization as a tool for assessment in 3.2 "Reusability of massive wood components" and 3.3 "Criteria for salvageability: the reuse of bricks" is a step to develop a generalized matrix for case-studies.

A third endeavor related to theory is substantiated in 4.1 "Salvageability; implications for architecture". The paper contributes to architectural theory about sustainable design by using the tectonic approach. Generally, "architectural theory" can be seen as normative and polemically oriented prescriptions of how to design buildings, and are only testable by measures of professional acceptance or longevity. They cannot be said to have the logical rigor of scientific theories as they can lead to a great variety of empirical outcomes (Groat et al. 2002). However, in this case, the search for an overriding theory can help place sustainable building in a context of architectural history and philosophy. For this purpose, it seems relevant to discuss the term *tectonic*. The tectonic approach may correspond to the sustainable approach in the sense that it stresses the importance of looking behind the surfaces of shapes, insists on coherency and overview, and addresses technical properties and processes as a significant source of design. The conclusion is that the term was found to be useful in linking the practical measures of environmental design in general and salvageability in particular with a principal theory on sustainable architecture. However, as further stated in sub-chapter 5.5 "future research", this attempt is as such only a small beginning.

To some degree, the findings also challenge accepted theory. The concept of *time related building layers* is frequently referred to in the core literature of DfD (see. e.g. Fletcher 2001, Crowther 2003, Durmisevic 2006). The concept is regarded as a principal system that should be adopted by the construction industry in order for DfD to become part of common practice, but the implications of the theory for constructions is generally not questioned. In 3.3 "Criteria for salvageability: the reuse of bricks" and 4.1 "Salvageability; implications for architecture", it is shown that whereas most other criteria for salvageability point to simplifications of building practices, the principle of building layers supports increased complexity. This was shown to pose dilemmas concerning several of the principles for salvageability. Therefore, the wording-of the criterion was rewritten, and *Suitable Layering* was proposed instead of *Layered Construction*. This stresses the point that in achieving salvageability, a layered construction may not be a goal in itself. Still, if the construction *is* layered, the layers should be structurally independent and also preferably organized in correct order regarding expected lifetime.

Thus, the thesis contributes mainly to expand existing practical knowledge. To some extent, the findings may also help develop some new theoretical grounds. In the case of the concept of *time related building layers*, the findings challenge accepted theory in the field of DfD.

5.2 Answering "Why"

This first study was not meant to answer the whole question of "why DfD", but aimed at making a contribution to the environmental rationale for facilitating reuse and recycling.

It seems like an obvious fact that the need for salvageable design is connected with the turnover of the components. Forecasting the possible turnover of both building and component layers before designing is generally a strategically important step in life cycle planning. However, scenario based predictions are coupled with uncertainty. A second argument, which was explored in this study, involves another mind-set; the environmental load of producing building materials should be credited with usability over time. Furthermore, since a long component lifetime presumably also involves changes during remodeling and rebuilding, high environmental investments call for a design that facilitates both renovations and potential new service lives for the components.

Hence, the more specific research questions questions were:

- *What technical lifetime of building structures can be seen as environmentally justifiable with regard to their material composition?*
- *Considering the average turnover of buildings, can the results from these calculations give some indications about the need for DfD for different material groups?*

Methodology:

- Quantitative assessment
- Discussion

The assessment that was performed to substantiate this argument used a simplified method for calculating the impact of ten different wall constructions. The indicator used was greenhouse gas (GHG) emissions related to extraction, production and transport of building materials.

ANALYSIS ON GHG-EMISSIONS OF EXTERIOR WALLS

The study explored the normative relationship between environmental impact and the lifetime of components. The concept of *environmental justifiable lifetime* was introduced. The accompanying logic is that the environmental loads of a material should be expected to be mirrored in a correspondingly long functional lifetime. A visualization of the (normative) relationship between building materials' embodied environmental load and their expected functional lifetime was presented. In retrospect, a diagram showing colour coded information about each wall contruction was prepared (figure 5.2.1).

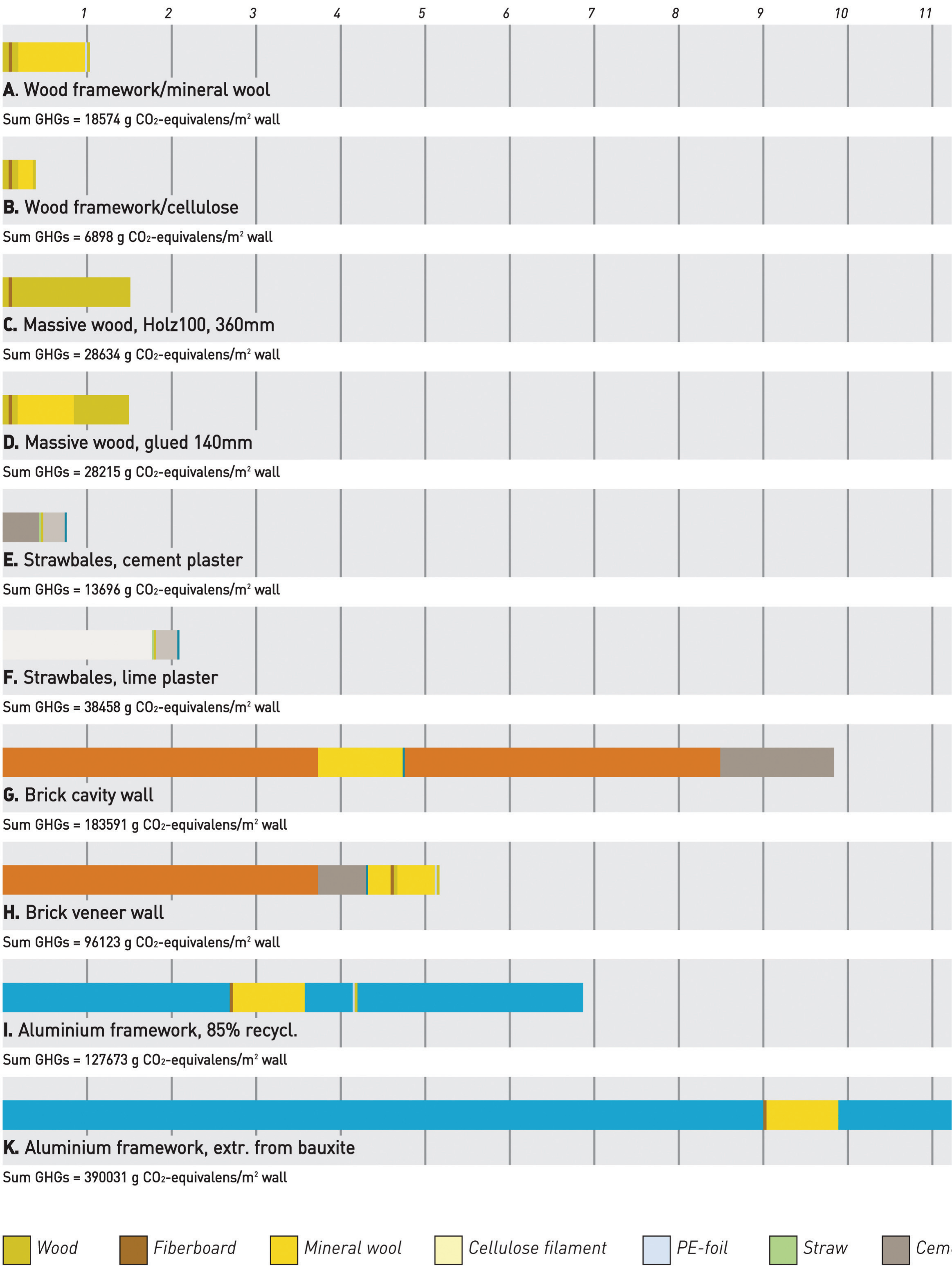
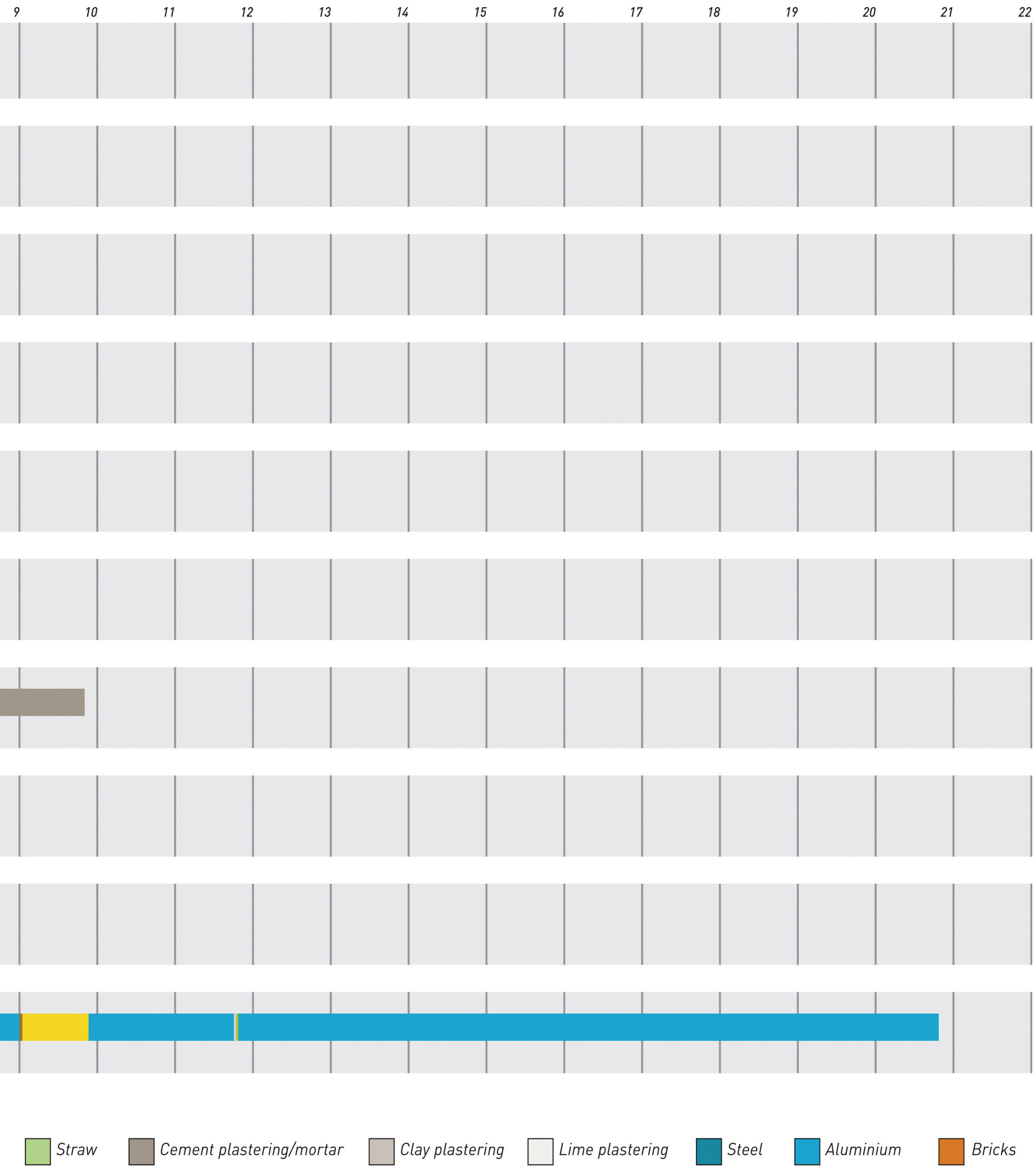


Figure 5.2.1: Environmentally justifiable lifetime, showed as number of expected building generations, for 10 exterior wall constructions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Straw
Cement plastering/mortar
Clay plastering
Lime plastering
Steel
Aluminium
Bricks

The method placed environmental impact of building materials as the point of departure for a calculation of expected lifetime, or “pay-back time”. It supposed an average lifetime of buildings’ structural parts of 50 years, and accepted the environmental load of wood framework (insulated with mineral wool) used for this time span. The calculations gave indications about how many times the structural components should be expected to fulfill a new service life. The comparative results revealed large differences in impact between the construction materials, and subsequently large differences in the need for salvageability. When it comes to the aluminium constructions, we should expect as much as 21 generations for the aluminium extracted from bauxite. This corresponds to a lifetime of 1050 years. One may question if using such a high impact material for the constructive parts of a dwelling is desirable from an environmental viewpoint. Anyhow, design for reuse/ recycling of such a construction is imperative.

A sketch for a possible assessment matrix for salvageability was presented (figure 5.2.2). Assessed environmental costs were seen to complement forecasted turnover as a point of departure for salvageable design. By intersecting turnover rate for the building part in question with its embodied environmental impact, the need for salvageability was visualized. A high score on both axes will demand a strategy of DfD. The need for salvageability is thereby connected to the specific material use. The calculation method that was used represents a quantifiable measure for expected building generations. This contribution can help enlarging the scope of salvageability.

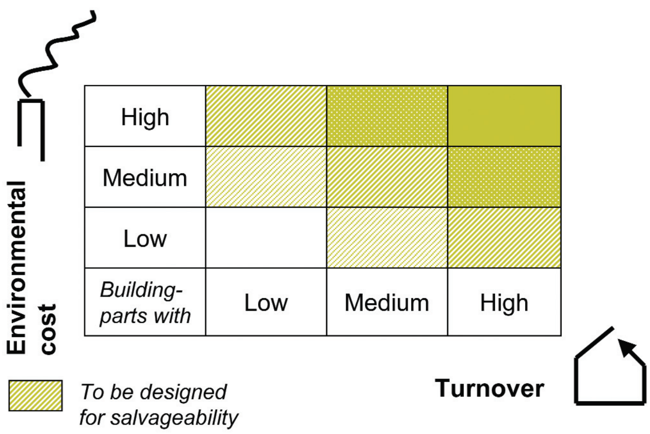

Figure 5.2.2: Need for demountable design assessment matrix

5.3 Answering "How"

Overriding question:

- *How can building design facilitate future deconstruction and salvage of materials?*

The potentials and limitations of different design solutions regarding salvageability were investigated. The task was divided in two steps. The first need was to analyse and operationalize the existing knowledge of Design for Disassembly. A principal systematization of DfD design guidelines and a tool for assessment were the outcome of 3.1 "Salvageabiliry of building materials". Then two case-studies were performed in 3.2 "Reusability of massive wood components" and 3.3 "Criteria for salvageability: the reuse of bricks". The second step thus explored the design principles and the assessment tool further.

The building materials chosen for the two case-studies each have an environmental rationale regarding salvageability. Massive wood has, in addition to the general environmentally beneficial properties of wood, a special potential for mitigating climate change through carbon storage. Bricks, on the other hand, are a good example of durable building units in need for environmental pay-back. However, the most commonly used massive wood components and brick constructions today are not designed for a second service-life of the components.

A second reason for choosing massive wood and brickwork for the cases-studies is that both material types have long traditions as building materials in Norway. Thus, the choice of material types enables a parallel study of historic building traditions. The functional units for both case-studies are chosen so that the compilation represents a historical development.

The case studies were different in that the first study explored a single component whereas the second study explored complete constructions, involving a range of materials and components. Findings and reflections regarding the assessment method follow the description of the two case-studies.

SYSTEMATIZATION OF GUIDELINES

Derivative questions:

- *How can the knowledge of DfD be operationalized into an assessment tool?*
- *What are the determining factors for this tool?*

Methodology:

- Literature review
- Critical reflection

3.1 "Salvageabiliry of building materials" consisted of an analysis of existing literature on DfD guidelines and assessment tools, and lead to a proposed, new systematization of guidelines. The design guidelines analysed were compiled from eight different studies, in which the number and level of detail of the guidelines, as well as the classification system, varied. Earlier studies have also introduced various assessment methods; however there is generally no direct connection between the specific design guidelines and the assessed parameters. The aim was to create a structured and consistent base of information, which could also be used for assessments.

A principal and multi-purpose systematization of DfD guidelines was prepared, dividing the guidelines into *scale* of application, main *criteria* and prescriptive *strategies* (see figure 3.1.1). The strategies were selected from the surveyed guidelines. As some strategies were regarded as more important than others, a prioritizing was performed. Strategies that are purely cost-linked, for example, were omitted. Focus is on environmental cost, which is regarded as not consistently reflected in the economic system. However, the matrix can be expanded to include other criteria and more strategies.

The system communicates both the basic criteria and the detailed strategies within three physical levels *(scale)* of investigation; the *component*, *construction* and *industry* level. The strategies can further be linked to various objectives according to the recycling hierarchy such as general dismantling for relocation, reuse or material recycling. The structured guidelines can be used as a base of information in various types of investigations as it is convertible to an assessment tool and can function as a checklist when designing salvageable components. The system may thereby become usable for design teams, contractors and manufacturers of building materials as well as to researchers and building authorities.

The criteria level is an independent contribution which summarizes the core points of the guidelines, and gives an easily comprehendible introduction to the field. The criteria are expressed as general performance standards, and are worded in a value based way so that the direction can be instantly understood. This level is therefore significant in a pedagogical context, and is used in all later articles.

All the investigated lists of design guidelines aimed at more or less the same goal: Material resource efficiency through facilitating reuse and recycling. The guidelines were thereby related to a range of processes of deconstruction, sorting, transport, new design and reassembly. Since the concept of Design for Disassembly basically reflects the disassembly phase, it was perceived as confined and misleading. The suggested replacement *Design for Salvageability* intends to include all lines of actions that contribute to salvage of building materials in one way or the other.

Limited material selection

1. *Minimise the number of types of material, preferably use monomaterial components*
2. *Minimise the number of, and types of, components and connectors*
3. *Avoid toxic and hazardous materials and secondary finishes*

Durable design

4. *Design durable components that can withstand repeated use*
5. *Pay attention to joints and connectors, and provide adequate tolerances for repeated disassembly and reassembly*
6. *Aim for aesthetic quality of components*

High generality

7. *Use standard dimensions, modular constructions and a standard structural grid*
8. *Aim for small scale and lightweight components*
9. *Reduce the complexity of components and constructions, and plan for using common tools and equipment*

Flexible connections

10. *Use reversible connections for subassemblies, between components and between building parts*
11. *Allow for parallel disassembly*

Suitable layering

12. *Design the layers of the construction as structurally independent systems*
13. *Arrange the layers according to the expected functional and technical lifecycles of the components*

Accessible information

14. *Provide identification of material and component types*
15. *Provide updated as-built drawings, log of materials used and guidance for deconstruction*
16. *Identify and provide access to connection points*

Figure 5.3.1: Check list for salvageability

As the principal systematization of the guidelines has become a comprehensive matrix, a short list was prepared in retrospect (figure 5.3.1). This list mainly aims at the design of components and buildings, and the levels are merged in order to get the message across in a simple way. The list also received a new strategy after reflecting on architectural measures in the last articles; *Aim for aesthetic quality of components.* Since this measure is believed to facilitate a long functional lifetime, the strategy was placed under the criterion *Durable design*.

CASE STUDY: MASSIVE WOOD COMPONENTS

Methodology:

- Case study, using assessment tool defined in 3.1 "Salvageability of building materials".
- Critical reflection

This case study investigated how component design influences reusability, and an assessment of massive wood component types was performed. The assessment represents a pilot study of using the design guidelines directly for an evaluation of building components.

Five Norwegian massive wood constructions were compared: log construction representing the vernacular tradition, customized massive wood components manufactured by Moelven and Holz 100 representing commonly used component types, and the modular components of Valdres Tremiljø and "Klimablokken" representing innovative designs. The relevant criteria within the component level were: *Limited Material Selection, Durable Design, High Generality, Flexible Connections*, and *Access and Information*. Following the assessment, aspects regarding each criterion were separately discussed.

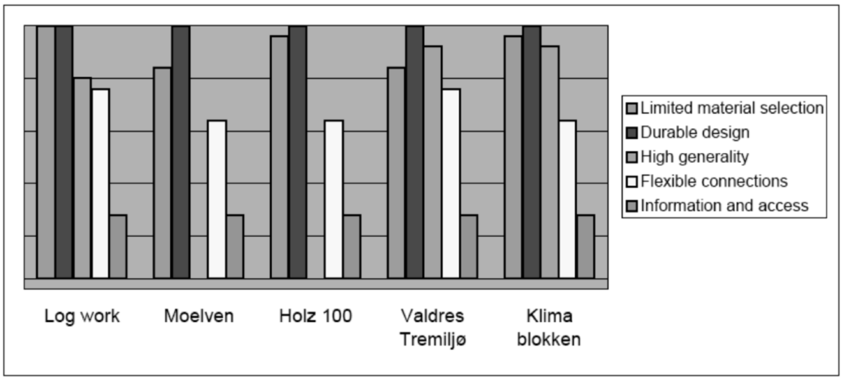

Figure 5.3.2: Assessment of massive wood components. Scores for each criterion, shown as clustered columns.

The results showed that the case objects differed from each other mainly for two criteria; *Limited Material Selection* and *High Generality* (figure 5.3.2). The scores for the criterion *Flexible Connections* did not vary much due to the fact that the component design in most cases was not decisive for the choice of connection methods. In all the five cases, both reversible and non-reversible connections could be used between components. The scores for the two criteria *Durable Design* and *Information and Access* were equal for all the five cases.

The large differences that were found for all the strategies within the criterion *High Generality* are seen as the most important finding. Simple and common construction methods, standard dimensions and small to moderately sized components aim at giving freedom of design in a second service life, whereas too large and specialized components can only repeat the same building. The case objects of Moelven and Holz 100 belong to the latter category, and therefore received zero points for this criterion.

Improved generality of the components will give architectural flexibility in a second service life, which is crucial to increase the likelihood of reuse. The study suggests that there is a great potential to improve the reusability for the most commonly used massive wood component types.

CASE STUDY: BRICKWORK CONSTRUCTIONS

Methodology:

- Case study, using assessment tool defined in 3.1 "Salvageability of building materials"
- Critical reflection

An assessment of reusability of brickwork was performed. The aim was to investigate how the component's design, as well as different construction methods, limits or supports the reusability. Two levels were addressed; Part A: The brick as a single component, and Part B: Complete brickwork constructions. The criteria for salvageability were used both as topics for discussion, and in an assessment matrix.

In Part A, the single brick was discussed for four aspects of component design. The criteria used were: *limited material selection, durable design, high generality* and *accessible information*. In addition to explaining the background for each criterion, the practical, technical and architectural consequences for the single brick with respect to the given strategies were investigated. Challenges as well as potentials were discussed.

In Part B, five external wall constructions were used to evaluate the potential for salvageability of different construction methods. "Trondheimshulmur", a 2 1/4 brick cavity wall, was chosen as an example of historic masonry laid with lime mortar. Then two commonly used masonry walls with contemporary thermal insulation standard and use of cement mortar (cavity wall and veneer wall), were selected from the Norwegian Building Research Design Sheets. Finally, two mortar-free masonry walls were collected from recently built projects; The IRCAM building in Paris from 1989, where bricks are used in a demountable external skin, and an experimental building in Japan with pre-stressed dry-masonry "SRB-DUP" as an insulated cavity wall. The four criteria used for assessing the salvageability at the construction level were: *limited material and component selection, suitable layering, high generality* and *flexible connections*. The background and the practical, technical and architectural consequences of the design measures for each criterion were later explained and discussed.

Unsurprisingly, as this point is well documented throughout history, the results of Part A showed that the single brick itself has great potential as a durable and reusable building component. The traditional brick may be characterized as an ideal component regarding most criteria for salvageability. Particularly, through simplicity and small scale, bricks possess a high generality, which eases integration in most building contexts. This architectural flexibility is an important prerequisite for a potential second service life.

The results of Part B showed that there are great variations between the five cases regarding the various criteria for salvageability (figure 5.3.3).

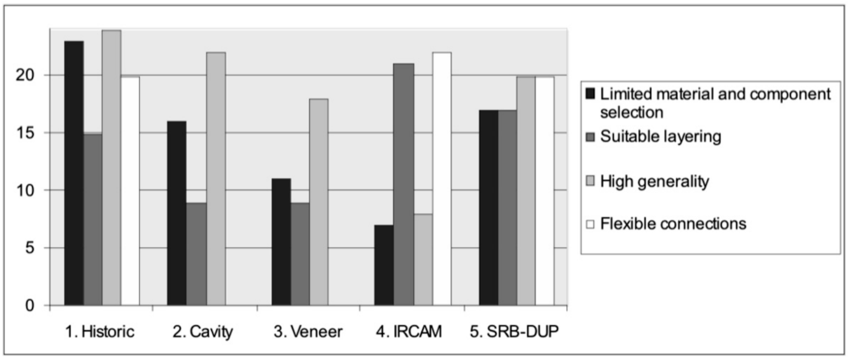

Figure 5.3.3: Assessment of brickwork constructions. Scores for each criterion, shown as clustered columns.

The two cases with cement mortar (cases 2 and 3) received zero points for flexible connections, and are unsuitable for salvage of bricks. The IRCAM building (case 4) received high scores for both *suitable layering* and *flexible connections*, but displayed many material types and customized designs with low generality. Since the criteria represent different aspects of salvageability, the scores are not added up. The cases must show good scores for every criterion to count as a salvageable construction.

Historic brickwork and the SRB-DUP system got the best overall scores. However, this result needs a discussion. The use of weak (lime) mortars and the use of metallic connectors have different consequences considering the environmental impact related to production. For the purpose of avoiding sub-optimizations in achieving overall environmental goals, the study suggests that further development of lime mortars is the most promising measure for salvageable brickwork.

The criterion *suitable layering* is closely related to the historic developments of brick constructions. The demand for better heat insulation resulted in a breakdown of the earlier integrated masonry. One of the lost qualities was flexible connections because the thinner brick veneer walls demanded strong mortars. However, the split also had negative consequences for other criteria for salvageability such as *limited material and component selection*. As a result of these discussions it became clear that a layered construction cannot be a goal in itself, and the wording of the criterion was rewritten.

The case study of the brick walls may be read as a history on sub-optimization. Therefore, when evaluating environmental effects of buildings today, care should be taken to ensure overall assessments. Topics like buildability, embodied energy, transportation and salvageability could be regarded as well as thermal properties, ventilation, moisture balance and air quality. In the endeavours of decreasing energy use for operation, building authorities set recurring stricter demands for thermal insulation. For the purpose of avoiding possible technical and environmental side-effects, more holistic studies could be useful to document the complexity and the full environmental effects of how buildings are constructed.

The prevailing financial framework conditions profitability for reuse and recycling. Decision-making in a single building project is usually based upon mere acquisition costs, but in order to make sustainable solutions not only environmentally but also economically viable, a lifecycle perspective must be used. Although the methodology for lifecycle costing (LCC) is limited in accounting for environmental, social and cultural costs involved in buildings, it may assist in focusing on long-term sustainability. Therefore, both environmental and financial considerations should be based on the lifecycle perspective and become compulsory exercises in the design phase of buildings.

A significant finding in the two case-studies is that in both the assessments, historical construction methods show very good results. This is not only due to high scores for *reversible connections*, but for all the criteria regarding salvageability. This leads to the reflection that the investigation of design guidelines for salvageability may be seen as a way of mapping tacit knowledge embedded in traditional building methods. Resource optimization is often an implicit quality of vernacular architecture, but this knowledge is not often explicitly forwarded. The criteria for salvageability may thereby describe and substantiate vernacular logic.

DISCUSSION OF THE ASSESSMENT METHOD

The research method used in the case-studies was based upon the structured guidelines for salvageability. The criteria were used both as topics for discussions and, together with the accompanying strategies, in the assessment matrix. As the criteria are considered to represent different aspects of reusability, they may vary in mutual importance from one assessment to the other. The results for each criterion were therefore presented separately, both in the discussions and in the quantitative results.

The prescriptive strategies give the most specific input for design solutions, and were used for individual scoring in the two assessment matrixes. The weighting of the strategies is an important factor for the quantitative result. Since the weighting is performed in relation to the objective of the assessment as well as the function of the case objects, the weighting of each assessment will vary. Furthermore, in weighting the strategies and in giving scores, different solutions will seem preferable depending on the context.

The assessment matrix showed to be a flexible system adaptable to various studies. Since the assessed parameters corresponded directly with the relevant strategies, the method gave transparency. However, there may be a mismatch between the degree of accuracy of the matrix and the more approximate estimate of the qualitatively given scores. Here, the two case-studies showed that an assessment at the construction level will be more subjected to rough estimates than at the component level.

The different experiences and viewpoints of the researchers will also affect the results. In an ideal situation, a team of professionals representing various experiences in the field of construction and deconstruction should perform the assessment. Multidisciplinary teams would guarantee more robust studies.

5.4 Answering "So what"

Overriding question:

• *What are the architectural consequences of salvageability?*

Methodology:

• Critical reflection, using the criteria defined in 3.1 "Salvageability of building materials"

Here, the aim was to couple the findings of earlier investigations with the field of architectural design. The study discussed in what ways the criteria for salvageability, as measures for sustainable construction, can be integrated as an innate part of the design process. An important motive was to bring research results closer to the sphere of interest among architects, and the overriding hypothesis is that the demand for salvageability of building materials may be seen as a positive driver for architectural design.

In exploring the architectural consequences of the design strategies, the tectonic approach appeared to represent a clue. The term *tectonic* implies using technological parameters as a source for design, and the concept was here expanded to include measures for responsible resource use. Thus, for this investigation, the tectonic approach was used as an instrument.

As in the case-studies in 3.2 "Reusability of massive wood components" and 3.3 "Criteria for salvageability: the reuse of bricks", the discussion was structured according to the criteria for salvageability. The principal criteria informing architecture are: *Limited Material Selection, Durable Design, High Generality, Flexible Connections, Suitable Layering* and *Accessible Information.* The study explored in what ways this field of knowledge may influence building practice and architectural expression, and pointed to building examples from past and present. The examples were chosen because they displayed design principles discussed in the text, but are not necessarily designed according to the principles of sustainable construction. Historical developments and practical consequences related to the criteria were also considered, and possible approaches to the different challenges they raise were suggested.

THE CRITERIA AS SOURCES FOR DESIGN

The studies showed that some criteria have greater consequences than others for the architecture. The most important findings were pointed out within the following three criteria:

• A *limited material selection* results in a homogenous architectural expression. In a settlement where only one or a few materials have dominated the buildings for centuries, different historical layers are connected. It may also create a basis for design simplicity, a well-known approach in the modernist tradition. A limited material selection makes it easier to investigate each building material at its own premises, which may give useful insights into technical as well as environmental qualities.

• *Flexible connections* can take a variety of shapes, and joints are often refined sections of the architecture in both vernacular and modern designs. Connection methods may be designed as integral parts of the components' structure and appearance, expressing transfer of loads not only physically but also in a figurative sense. The principles for the joining of the components also determine the premises for a possible patterned ornamentation of the surfaces. If the aesthetical language is rooted in these patterns, a tectonic relation between the material qualities and the architectural expression is enabled.

• *Accessible Information* is useful knowledge regarding salvageability that can be carried along with the components as well as along with the architectural language. Product information may indicate raw material types and qualities as well as company name, production site and year. In addition to the purely technical advantages, tagging or moulding has the potential to add texture/ relief that may contribute to distinctive architectural expressions. At the building level, the architectural language may also function as a conveyor of useful knowledge, tacitly related to the readability of the construction. Simple construction methods, integrated functionality of components and the use of monomaterials facilitate this readability.

Quality of design may in its own right be a facilitator for long functional lifetimes. Although there are many opinions about what is good design, clever detailing might increase the affection value and provide for long-term relationships with the users. Thus, the chances are great that both the whole building and the components themselves will be maintained and reused by the owners so that an environmentally responsible resource use is achieved.

A process oriented building practice may, however, challenge the prevailing view on architectural design. Popular approaches pursue architecture as original and artistic expressions influenced by changing fashions, and these characteristics do not fit well with the criteria for salvageability. The prototypes for lifecycle design are rather available in vernacular traditions, and consist of building *patterns*. These considerations point to a more conservative design philosophy, where *generality* of both components and floor plans is essential. As opposed to materializing recurring new design ideas on a large scale, it is advisable to start out with general structures that give a set of options for occupation. In adapting to the users' specific needs over time, each building's uniqueness will instead appear during use.

The tectonic approach was found to be useful in the context of salvageability, and in exploring the implications for architecture. Tectonics bypasses the question of architectural style, and may be conceived as a practical concept in discussing sustainable measures for buildings. Merging technological and aesthetical challenges, the logic of the components is acknowledged as a premise for architectural design. This logic considers the quality and characteristics of different materials, extraction and production terms, and recycling potential. An investigation into this logic may create a knowledge base for achieving the best possible use of resources in a life cycle perspective. Following the tectonic approach, environmental efficiency may be forwarded into component shape and connection details and subsequently become a premise for construction and deconstruction.

Although much of the building mass produced in the last century can be said to reflect overconsumption and a *linear* resource use, there is a strong public consensus today that environmental measures must be taken in the building trade. Environmental considerations could, in addition to forwarding purely practical measures, also influence architectural expression. As the issue of salvageability has strong implications for architectural design, the criteria could contribute in manifesting sustainable thinking at the "molecular" level of constructions.

5.5 Future research

The chapters "WHY", "HOW" and "SO WHAT" map out various aspects of salvageability that may all be continued and supplemented in future research. Generally, in attempting to solve the complex environmental challenges in the building sector, I believe that research questions reflecting a wish to optimize practice by asking "what is the best we can do", are more intriguing and have better chances of finding future-oriented solutions than the more defensive questions of "how can we do things less bad".

The discussion of environmental rationale was summarized in figure 2.1.7. Here, the horizontal axis show the expected turnover of building components, and the vertical axis show their corresponding environmental impact. The diagram is principal in character, and the possible scores indicate the need for demountable design - or salvageability. A study recently performed by SINTEF Building and Infrastructure ("GLITNE Gjenbruk") takes this diagram as a point of departure and surveys building components with high scores on both axes. The SINTEF project uses more comprehensive methods for environmental assessments and bases turnover on empirical data collected from stakeholders in the building trade. This system may, in the end, serve as a data base for design decisions regarding salvageability. It may be expanded to include more data and may need continuous updating.

Generally, I believe that there is a substantial base of knowledge for designing salvageable buildings. A proactive approach in turning the strategies into actual constructions does seem like the obvious proposal for the next step to take. Initiatives like the lifecycle building challenge design competition for students and professionals (see www.lifecycle-building.org) show a promising attempt to forward building components and methods aimed at material resource efficiency in the whole lifecycle. In Trondheim, the development of the Stavne timber block is a specific, local initiative to develop an optimized building component in massive wood. Since massive wood components now are being introduced at a large scale in Norway, it seems timely to discuss this building method in a life cycle perspective. Every design process is unique and in many ways it resembles a research process. Thus, when design investigations are coupled with systematization and the possibility of later verification, they may be reported as research, or more precisely as *research by design*. I believe the matrix for salvageability may be useful as a check-list in such design processes.

For further discussions of *how*, more case-studies could assist in widening the understanding of salvageable designs. Case-studies of other material and component types and maybe also of whole building constructions could e.g. assess whether or not it is a stable trend that historical building methods generally have high overall scores whereas more contemporary cases have a tendency towards more uneven scores for the different strategies. This could help reveal possible sub-optimizations resulting from pursuing single measures in building constructions. Regarding the present emphasis on the *passive house* as a major architectural response to the climate challenge, holistic research that addresses a set of environmental issues in the whole life cycle seems essential.

Architectural consequences can be seen from both a practical and a theoretical side. In the last paper, the concept of tectonics is used in describing the design measures for salvageability. It is also suggested that this notion may be used in a broader context in describing environmental design measures in general. The idea is only briefly pursued in the thesis, but further investigations could aim at substantiating tectonic thinking in reflecting overall environmental goals.

references and list of figures

6.0

6.0 References and list of figures

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LIST OF FIGURES

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acknowledge-ments 7.0

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attachments

8.0

8.1
Byggematerialer: klima-belastning, miljømessig forsvarlig levetid og design for gjenbruk

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ANNE SIGRID NORDBY,
BJØRN BERGE, ANNE GRETE HESTNES

Byggematerialer:

klimabelastning, miljømessig forsvarlig levetid og design for gjenbruk

Design for gjenbruk av byggematerialer er en strategi for å lette ombruk og gjenvinning av materialer etter endt funksjonell levetid. Spørsmålet er om denne strategien nødvendigvis har et miljømessig rasjonale for alle typer bygninger og for alle byggematerialer.

Kan man låne begreper fra finansverdenen og betrakte miljøinnsatsen i produksjonen av byggematerialer som en investering? Kan nedbetalingstid oversettes til teknisk kvalitet på komponentene? Og er dette en grunn til at komponenter med høy miljøbelastning bør detaljeres slik at gjenbruk kan muliggjøres?

Gjennom en analyse av klimabelastningen for ti ytterveggskonstruksjoner introduseres begrepet *miljømessig forsvarlig levetid*. Artikkelen argumenterer for å vurdere komponentenes miljøbelastning så vel som deres potensielle omløpshastighet i forbindelse med detaljeringen av konstruksjoner.

Rundt 80 % av avfallet fra norsk byggeindustri sendes til deponi, ca. 10 % brennes og bare ca. 10 % blir gjenbrukt i en eller annen form.[1] En viktig parameter for det lave gjenbrukspotensialet er knyttet til design: Der vi tidligere hadde et relativt beskjedent antall velkjente byggematerialer, har vi nå flere hundre tusen, sammensatt av diverse former for bearbeidede råmaterialer og en rekke tilsetningsstoffer. Videre er komponenter av ulike materialer og kvaliteter ofte permanent sammenføyd, og tekniske installasjoner ofte integrert i konstruksjonen. Dermed blir søppelfyllingen, eller muligens forbrenning eller knusing til fyllmateriale, det eneste alternativet når komponentene har tjent sin funksjon.

Bransjen er dessuten preget av kortsiktighet, og omløpshastigheten for bygninger og bygningsdeler øker stadig. Den dårlige ressurshåndteringen har negative miljømessige konsekvenser i begge ender av materialflyten: Presset på råmaterialer øker, mens avfallsbehandling blir et økende problem, med voksende fyllinger og utslipp av giftstoffer. Og på veien fra vugge til grav forbruker utvinning, bearbeiding og transport av materialer store mengder energi.

Til tross for disse negative tendensene, har vi eksempler på gjenbrukshus i betydningen bygninger bygget av ombrukte materialer. En opplagt motivasjon er økonomiske besparelser, men vi ser også eksempler på at gjenbruk betraktes som en merverdi fordi man eksponerer historisk interessante bygningsdeler eller signaliserer miljøbevissthet. Gjenvinning av skrapjern og knusing av betong til veifyllinger har lenge vært praktisert, noe som viser at det er økonomi i hvert fall i deler av gjenvinningsindustrien.

Imidlertid er det store forskjeller i eksisterende bygningsmasse når det kommer til *gjenbrukbarhet*. Etterkrigsarkitekturen er generelt ikke prosjektert med tanke på demontering for ombruk eller gjenvinning, mens eldre bygninger faktisk var nettopp det. Teglkonstruksjoner med kalkmørtel, som var vanlig for 100 år siden, er i høyeste grad gjenbrukbare. Også tradisjonelle laftehus kan sies å være formgitt med tanke på demontering og gjenbruk. Disse var forberedt for utskifting av enkeltelementer, ombygninger og flytting av hele hus. Dessverre har vi ikke klart å overføre disse designprinsippene til moderne byggeindustri.

DESIGN FOR GJENBRUK

Erfaringer viser at ulike deler eller *sjikt* av bygningen skiftes ut med ulik hastighet. Mens bærekonstruksjonen kan vare i 60 eller for den saks skyld 200 år, må ytterkledninger skiftes ut etter 20-30 år og installasjoner for el, vann og luft gjerne etter 7-15 år. Derfor har vi lært at en tilpasningsdyktig bygning må bestå av friksjonsfrie sjikt, slik at komponentene kan operere uavhengig av hverandre.[2] Dette gir fordeler i to typer sammenhenger: Der komponentenes levetid av tekniske eller funksjonelle årsaker er kortere enn byggets levetid, vil vi oppnå en brukervennlig fleksibilitet. I det motsatte tilfellet, der komponentenes tekniske kvalitet overgår bygningens levetid, legges det til rette for ombruk og gjenvinning av materialer.

Ulike studier har introdusert og diskutert begrepet *Design for Disassembly / Deconstruction* (DfD) som et hovedmål for å redusere miljøbelastningen for bygninger.[3] DfD innebærer at komponenter og konstruksjonsmetoder tilrettelegges for demontering og gjenbruk, og ses som en strategi for å redusere livssyklus-kostnader så vel som miljøbelastning. Gitt holdbare og optimalt formgitte komponenter, samt en byggeindustri som er orientert mot ombruk og gjenvinning, kan man se for seg et antall livsløp for komponentene som er bedre relatert til deres tekniske kvalitet. Den norske oversettelsen «Design for gjenbruk» fokuserer på miljøge-

FIGUR 1.
KLIMABELASTNING PR. KVM FOR TO YTTERVEGGER I TRESTENDERVERK.

A
Trestenderverk/Rockwool **18574** g CO_2-ekv/m2 vegg.

- 5% Ytterpanel, 22 mm
- 0% Lekter 20x36 c/c 600
- 4% Vindtettplate Hunton
- 8% Trestender 48x223 c/c=600
- 78% Rockwool A (37) 223mm
- 2% PE-folie
- 3% Innv. panel 15 mm

B
Trestenderverk/ cellulose **6898** g CO_2-ekv/m2 vegg.

- 13% Ytterpanel, 22 mm
- 1% Lekter 20x36 c/c 600
- 10% Vindtettplate Hunton
- 20% Trestender 48x223 c/c=600
- 47% Cellulosefiber
- 9% Innv. panel 15 mm

ENERGIBRUK I LIVSSYKLUSEN
På grunn av stadig høyere isolasjonsstandard vil bygningenes energibehov til drift reduseres. Dermed kommer energibehovet for materialer til å utgjøre en større andel av det totale energibehovet gjennom livssyklusen i framtidens byggeri.
I en svensk undersøkelse er denne andelen beregnet til ca. 70% for materialbruk i lavenergiboliger når råvareressursene for energiproduksjonen er inkludert.
40–50% av dette kan spares inn ved gjenbruk. [9]

Det er store forskjeller i eksisterende bygningsmasse når det kommer til gjenbrukbarhet. Her riving av hudavdelingen fra 1800-tallet ved St. Olavs hospital i Trondheim 2005, der mye teglstein ble ombrukt gjennom arbeidsforetaket ReBygg ved Stavne Gård.
Existing buildings vary widely with regard to reuseability. Above the demolition of the dermatology department of St. Olav's Hospital in Trondheim, where much of the brick was reused.
FOTO: ROLF A. BOHNE

vinst, og tydeliggjør dermed at strategien inkluderer flere aspekter enn demonterbarhet.

MILJØMESSIG RASJONALE

Historisk sett har «Design for gjenbruk» vært praktisert i ulike sammenhenger fra tradisjonelle nomadetelt til paviljongene på ulike verdensutstillinger og i futuristiske prosjekter signert Buckminster Fuller eller Archigram. I dag er ressursperspektivet en hovedmotivasjon. Man kan imidlertid sette spørsmålstegn ved om denne strategien nødvendigvis har et miljømessig rasjonale for alle typer bygninger og for alle byggematerialer. Et opplagt vurderingskriterium er komponentenes antatte omløpstid. Behovet for fleksibilitet kan avdekkes gjennom scenariobaserte analyser; hvis prognosene antyder høy grad av utskifting, vil vi oppnå både økonomiske og miljømessige fordeler gjennom å planlegge med tanke på fleksibilitet og gjenbruk.

Vi forslår at man i tillegg til å analysere elementenes omløpshastighet bør vurdere materialenes miljøbelastning. Et utgangspunkt er da at komponenter med høy miljøbelastning kan forsvares med en lang teknisk holdbarhet, på samme måte som man gjerne beregner lengre tilbakebetalingstid hvis man låner større beløp i en bank. Komponenter med lang levetid er miljømessig gunstige fordi presset på nye råmaterialer samt avfallsbelastningene reduseres. Ettersom bygninger nå rives i stadig raskere takt, må imidlertid komponenter produsert for en lang levetid og med høy miljøinnsats forberedes for reisen. Utformingen må muliggjøre potensielle nye livsløp.

ANALYSEMETODE

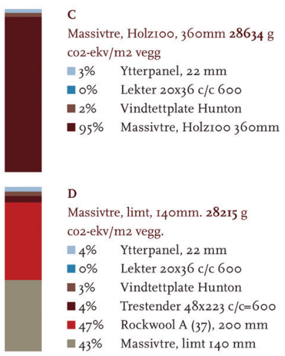
I dette forskningsprosjektet er miljøbelastningen beregnet for ti ytterveggskonstruksjoner (fem konstruksjonsmaterialer, hvert av dem anvendt i to versjoner) som alle på et eller annet vis er lansert som miljøvennlige alternativer i forbindelse med boligbygging. Funksjonell enhet er satt til 1 kvm komplett yttervegg med U-verdi 0,20 (W/kvmK), og som indikator for miljøbelastning benyttes klimagassutslipp, målt i CO_2-ekvivalenterer. Utslipp er beregnet for hvert materialsjikt gjennom utvinning av råvarer, produksjon av komponenter og transport til byggeplass. Resultatet uttrykker dermed en «dag 0»-situasjon (*Vugge til port-analyse*), der verken driftsenergi, CO_2-binding eller økonomiske vurderinger er inkludert. Transportdistansene er estimert som gjennomsnittlige for norske byggematerialer,[4] og data for klimagassutslipp er i hovedsak levert av Sintef-Byggforsk.

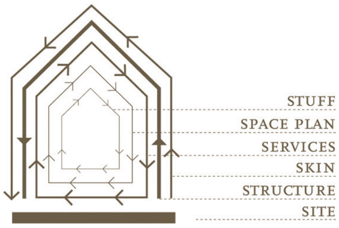
TRESTENDERVERK

Trestenderverk isolert med mineralull kan vel sies å være den mest typiske ytterveggskonstruksjonen anvendt i norsk småhusbygging. De fleste sjiktene, konstruktive elementer så vel som utvendig og innvendig kledning, består av trebaserte materialer. Tre som byggemateriale har lange tradisjoner her til lands; det å velge tre på grunn av miljøvennlighet er imidlertid en relativt ny motivasjon. Men uansett: Listen over gode argumenter er lang. De fleste steder er tre et lokalt materiale, det er en fornybar ressurs, det er lett og allsidig anvendbart i de fleste bygningselementer, det gir godt inneklima. Og med riktig detaljering kan det vare i århundrer.

I vegg A genererer mineralull-sjiktet den største andelen av klimabelastningen. Når vi erstatter mineralull med cellulosefiber i vegg B, synker den samlede belastningen betraktelig. Cellulosefiber er laget av resirkulert avispapir og er et foretrukket isolasjonsmateriale for

FIGUR 2
KLIMABELASTNING PR. KVM FOR TO YTTERVEGGER I MASSIVTRE.





ØKENDE OMLØPSHASTIGHET
Gjennomsnittlig omløpstid for et høyhus i Tokyo på 1980-tallet var bare 17 år! Også innenfor boligbygging i Skandinavia øker omløpshastigheten: I løpet av de siste 7–8 år var 25 % av alle leilighetshus som ble revet i Sverige, yngre enn 30 år.[10] Innenfor en husgenerasjon vil imidlertid ulike deler av bygningen skiftes ut med ulik hastighet.

mange miljøbevisste husbyggere. Det er imidlertid tilsatt boraks som brannhemmende middel, og dette er definert som en miljøgift på SFTs OBS-liste. Miljøbelastningen for vegg B bør derfor vurderes høyere enn det en klimagassanalyse er i stand til å formidle.

Massivtre gir nye muligheter til å tenke modulbygging og endringsdyktighet. Elementer fra Valdres Tremiljø er skrudd sammen av 34 x 120 mm bord i fire eller fem lag, og har en bredde på 360 mm. Elementene skjøtes med not og fjær, og kan brukes i både vegg, dekke og tak. Enkel materialbruk, demonterbarhet og en modulbasert utforming i relativt liten skala gjør elementene langt mer gjenbrukbare enn store, skreddersydde og limte elementer.
Solid timber elements offer new possibilities in design for modulated construction and reusability. Elements from Valdres Tremiljø are bolted together from four or five layers of 34 x 120 mm planks, up to a width of 360 mm. They are toungue-and-groove jointed, and can be used in walls, floor slabs and roofs. Simple use of materials, demountability and small-scale modules makes these elements much more reuseable than larger tailor-made or glued elements.
FOTO: MIKAEL ØVERGAARD

MASSIVTRE

Massivtre er blitt introdusert i løpet av de siste 10–15 årene som et alternativ til betong. I tillegg til den generelle grønne reklamen for tre, er stikkordene her varme- og fuktstabilisering samt CO_2-binding. Holz 100-konseptet anvender riflede bord i limfrie forbindelser, og elementene oppnår gode isolasjonsegenskaper.

Den totale klimabelastningen for de to massivtre-alternativene er grovt sett like høy. CO_2-ekvivalenter fra vegg C stammer utelukkende fra trematerialer. Selv om tre generelt har lav klimabelastning fra produksjon, genererer tung og lang transport en anselig mengde CO_2. Med en lettere bærekonstruksjon i massivtre som isoleres utvendig, er vegg D en rimeligere og mer vanlig utførelse. Prinsippene for denne løsningen er blant annet anvendt i Brendeland & Kristoffersens boliger på Svartlamoen i Trondheim (se BK 6–2004 og 6–2005). Ca. halvparten av klimabelastningen i vegg D stammer fra mineralull, mens belastningen fra massivtreet er redusert tilsvarende.

HALM

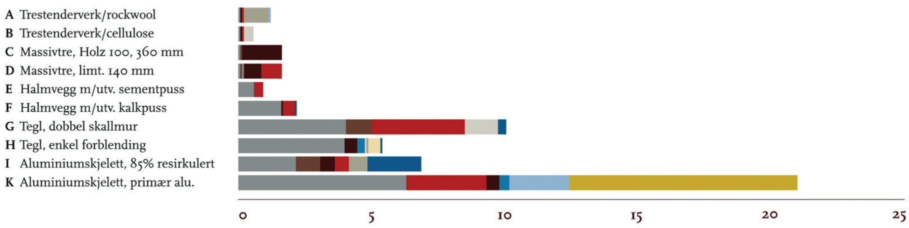
Halm er i mange bygder et lokalt avfallsprodukt. Ressurstenking hånd i hånd med lave kostnader, meget god isolasjonsevne, stor brannmotstand, enkel byggeprosess og gode innemiljøegenskaper har gjort halm til et interessant alternativ i et voksende antall økologiske pilotprosjekter. Bygging med halmballer er velegnet for egeninnsats, og en rekke hus er oppført på dugnad i regi av Norsk Jord- og Halmbyggerforening, som samtidig samler erfaringer om bruken av dette materialet.[5] Internasjonalt er det en raskt voksende byggemetode, og halm er også benyttet i større prosjekter, bl.a. av den prisbelønte arkitekten Sarah Wigglesworth i Storbritannia.

Halmen har i seg selv en ubetydelig miljøbelastning, det er de to nødvendige puss-lagene som i første rekke genererer klimautslipp. Begge ytterveggene har innvendig leirepuss. Utvendig har vegg E konvensjonell sementpuss, mens vegg F har kalkpuss. Kalk er ansett som et teknisk bedre alternativ enn sement til pussing av halmvegger fordi den er mer diffusjonsåpen og elastisk. Imidlertid viser det seg at CO_2-utslippene fra produksjonen av kalk er høyere enn for sement. Her bør det kommenteres at både sement og kalk over et 60 års livsløp binder tilbake (gjennom karbonatisering) hhv. 75 % og 95 % av de CO_2 utslippene som genereres under produksjonen.[6] Hadde beregningene tatt for seg hele konstruksjonens livsløp, ville dermed dette forholdet endret seg til fordel for kalk.

TEGL

Tegl som byggemateriale har lange tradisjoner. Brenning av leire til teglstein krever store mengder energi, men resultatet er styrke og holdbarhet. Teglkonstruksjoner kan vare i tusen år. Den ferdigbrente teglsteinen er emisjonsfri, og materialet gir en varme- og fuktstabilisering som er gunstig for inneklimaet. Som en småskala arkitektonisk byggekloss er den høyst allsidig, og (avhengig av mørteltype) fleksibel for ombruk i et utall bygninger.

FIGUR 6: MILJØMESSIG FORSVARLIG LEVETID MÅLT I ANTALL HUSGENERASJONER. FOR 10 YTTERVEGGSKONSTRUKSJONER.



Vegg G er en skallmurkonstruksjon, der to teglvanger er adskilt med et drenert og isolert hulrom. Vegg H representerer en mer alminnelig anvendelse av tegl der et forblendingssjikt dekker en bakenforliggende konstruksjon, her i trestenderverk. Tegl, mørtel og puss genererer den største andelen klimabelastninger i begge konstruksjonene, henholdsvis 90 % og 83 %.

ALUMINIUM

Bruken av aluminium til bygningsformål er relativt ny. Utvinningen fra bauxitt krever store mengder energi, og utslippene av klimagasser for primærproduksjonen er derfor høye. Imidlertid har aluminium god korrosjonsbestandighet, lang holdbarhet, det har lav vekt og er egnet for presis detaljering. Og fremfor alt i denne sammenhengen egner det seg svært godt til materialgjenvinning. Når metallet smeltes om, behøves bare 5 % av energien som ble brukt under utvinning. Et eksempel på et aluminiumshus som er interessant i et livssyklus-perspektiv, er Løvetann-prosjektet til Snøhetta / Hydro / Siemens. Leverandørene har som målsetting å tilby boliger med tydelig miljøprofil og individuelt tilpasset design, og modulsystemet er basert på rammeverk i aluminium. Fasaden har videre en sekundærstruktur i aluminium og fleksible fasadepaneler.[7]

Vegg I består av 85 % resirkulert aluminium og vegg K av primæraluminium, ellers er sjiktene identiske. Aluminiumsdelene genererer henholdsvis 87 % and 97 % av de totale klimagassutslippene.

SAMMENLIGNING AV RESULTATER

Det konvensjonelle trestenderverket isolert med mineralull er med sine 18574 g CO_2 ekvivalenter pr. kvm valgt som referanse-enhet. Forventet funksjonell levetid for en bolig er satt til 50 år, og dette er vist som én hus-generasjon i figur 6. Resultatene for de andre konstruksjonene viser hvor mange generasjoner hver yttervegg bør kunne forventes å vare, eller deres *miljømessig forsvarlige levetid*.

Både trestenderverk, massivtre og halmvegger ligger, grovt sett, lavt når det gjelder klimabelasting. Ikke overraskende finner vi teglvegger et stykke høyere opp. Følgelig bør vi kunne forvente oss 5–10 hus-generasjoner for teglstein, og ved bruk av kalkmørtel er dette også fullt oppnåelig for tegl av god kvalitet. Når det gjelder aluminium, ser vi at det er stor forskjell i klimabelastning mellom det primære og det resikulerte materialet. Mens en miljømessig forsvarlig levetid for resirkulert aluminium kan ligge på ca. 7 husgenerasjoner, bør vi kunne forvente så mye som 21 generasjoner for konstruksjonen av primæraluminium. Dette tilsvarer en levetid på drøyt 1000 år, og en kan spørre seg om det fra et ressursmessig ståsted kan forsvares å bruke et så høyt belastende materiale til en bygnings konstruktive deler. Uansett burde design for gjenbruk her være en selvsagt premiss.

Ulike materialer har ulike potensialer ved slutten av første hus-generasjon. Tre og andre biomassematerialer har en rekke muligheter: Komponenter kan ombrukes, materialet kan resirkuleres til fiberplater osv. eller vi kan oppnå varmegjenvinning gjennom forbrenning. Murverk kan, avhengig av mørteltype, ombrukes i gjentatte hus-generasjoner, imidlertid er det mer vanlig å knuse tegl og betong til fyllmateriale. Metaller kan også ombrukes, men blir som regel isteden smeltet om til nye produkter. I et ressursperspektiv er ombruk å foretrekke framfor materialgjenvinning. Knusing og omsmelting forutsetter energikrevende prosesser og

FIGUR 3: KLIMABELASTNING PR. KVM FOR TO YTTERVEGGER I HALM.

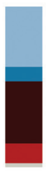
E
Halmvegg m/sementpuss **13696** g co2-ekv/m2 vegg

- 60% Puss-mørtel, sement 20 mm
- 3% Halm 450 mm
- 1% Dymlinger
- 34% Leirpuss 20mm
- 2% Armeringsnett, kyllingnetting

F
Halmvegg m/kalkpuss **38458** g co2-ekv/m2 vegg

- 86% Puss-mørtel, kalksement 20 mm
- 1% Halm 450 mm
- 0% Dymlinger
- 12% Leirpuss 20mm
- 1% Armeringsnett, kyllingnetting

FIGUR 4: KLIMABELASTNING PR. KVM FOR TO YTTERVEGGER I TEGL.

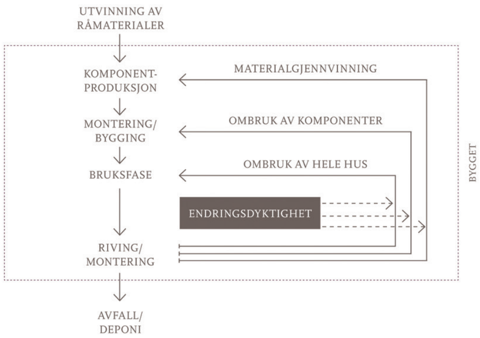


G
Tegl, dobbel skallmur **183591** g co2-ekv/m2 vegg

- 38% Mangehulltegl, rød. 1/2 steins vange
- 10% Rockwool Murplate (34) 187,5 mm
- 0% Stålbindere, Ø=4mm. 4 stk.
- 38% Mangehulltegl, rød. 1/2 steins vange
- 12% Mur-mørtel (sement) 2 vanger
- 2% Puss-mørtel sement 10 mm

H
Tegl, enkel forblending **96123** g co2-ekv/m2 vegg

- 72% Mangehulltegl, rød. 1/2 steins vange
- 11% Mur-mørtel (sement) 1 vange
- 0% Stålbindere, Ø=4mm. 4 stk.
- 5% Rockwool Murplate (34) 50 mm
- 1% Vindtettplate, Hunton
- 1% Trestender, 48x125 c/c=600
- 9% Rockwool A (37) 125 mm
- 0% PE-folie
- 1% Innv. trepanel, 15mm



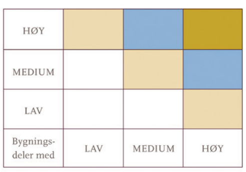
GJENBRUKSHIERARKIET
Diagrammet viser materialflyten gjennom de ulike fasene av en bygnings livsløp. Ved gjenbruk av byggematerialer igangsettes kretsløp slik at både behov for ressurser inn til systemet og avfall ut reduseres. Kretsløpene fungerer hierarkisk: Jo mer bearbeiding, jo mer tilførsel av ny energi og råmaterialer vil kreves, og jo mindre sitter vi igjen med av den opprinnelige ressursen. Ombruk av komponenter i samme form og med minimal bearbeiding (f. eks. av dører og vinduer) er derfor miljømessig mer fordelaktig enn materialgjenvinning (f. eks. omsmelting av metaller og knusing av betong). En viktig drivkraft for gjenbruk er design og teknologi som muliggjør fleksibilitet, her kalt endringsdyktighet.

FIGUR 5: KLIMABELASTNING PR. KVM FOR TO YTTERVEGGER I ALUMINIUM.

I
Aluminiumskjelett, 85% resirk. **127673** g co2-ekv/m2 vegg
- 26% Utv. aluminiumsbekledning, 3 mm, 85% resirk.
- 13% Aluminium B-ramme, 85% resirk.
- 1% Vindtettplate, Hunton
- 8% Rockwool A (37), 150mm
- 5% Rockwool lyd (34), 50mm
- 8% Aluminium A-ramme, 85% resirk.
- 0% PE-folie
- 0% Innv. trepanel, 15 mm
- 39% Aluminiumskjelett, 85% resirk.

K
Aluminiumskjelett, primær alu. **390031** g co2-ekv/m2 vegg
- 29% Utv. alu. kledn., 3 mm, primær alu.
- 15% Aluminium B-ramme, primær alu.
- 0% Vindtettplate, Hunton
- 3% Rockwool A (37) 150 mm
- 2% Rockwool lyd (34) 50 mm
- 9% Aluminium A-ramme, primær alu.
- 0% PE-folie
- 42% Aluminiumskjelett, primær alu.

FIGUR 7: «DESIGN FOR GJENBRUK», VURDERINGSMATRISE.



ev. tilleggstransport, og som resultat får vi produkter med lavere kvalitet enn de opprinnelige.

DISKUSJON

Det synes opplagt at gjenbruk, da spesielt ved direkte ombruk av komponenter, i mange tilfeller vil gi miljømessige fordeler. På den annen side er det langt fra opplagt at gjenbruk vil føre til noen økonomisk vinning innenfor det økonomiske og juridiske rammeverket byggeindustrien har i dag. Det vi imidlertid bør være oppmerksom på, er at dette rammeverket er i stadig endring. Avgifter for avfallsdeponering vil sannsynligvis fortsette å stige, og lovreguleringer som kontrollerer avfallsstrømmene vil definitivt skjerpes. I andre bransjer har man pålagt produsentene plikt til innsamling og gjenvinning av varer, dette gjelder i dag for elektriske og elektroniske produkter og det er under implementering i bilbransjen. Forlenget produsentansvar gir sterke insentiver til å utforme produkter med lang holdbarhet og maksimal gjenvinnbarhet etter første generasjons bruk, og kan radikalt endre produksjon og leveranse av varer.[8] Med byggebransjens avfallsproblemer i bakhodet er det liten grunn til ikke å vurdere slike tiltak også for byggematerialer.

Man kan spørre om ikke «Design for gjenbruk» i enkelte tilfeller burde påkreves, på samme måte som vi har satt krav til energibruk i bygninger. Matrisen i figur 7 visualiserer to viktige momenter som en slik vurdering bør inneholde. På den horisontale aksen settes komponentenes forventede omløpshastighet, som erfaringsmessig avhenger av både lokalisering, bygningstype og bygningsdel/-sjikt. På den andre aksen måles komponentenes miljøbelastning. Eksempelvis bør dermed en fasadekledning i kobber på et kontorbygg i Bjørvika i høyeste grad formgis med tanke på gjenvinning av materialet, mens problemstillingen for en bærekonstruksjon i stampet jord på Mysen ikke vil være like presserende.

Ut fra dette resonnementet kan man se for seg en arkitektur der målet for materialbruken blir å anvende rett komponent på rett sted til rett tid og på riktig måte. Kanskje tilnærmingen kan kalles materialtilpasset livsløpsdesign? Sikkert er at hvis vi skal bevege oss i retning av en bedre ressurshåndtering i byggebransjen, bør den glansbilde-arkitekturen vi har sett mye av til nå, erstattes av en mer prosessorientert byggeskikk.

ANNE SIGRID NORDBY

Artikkelen er et utdrag av en tidligere publisert artikkel i *Proceedings of the Global Built Environment: Towards an Integrated Approach for Sustainability* (2006, editor: M. Mourshed, 8 sider), tilgjengelig fra http://www.ab.ntnu.no/bht/ansatte/nordby.html. Den ble presentert på The Global Built Environment Conference i Preston, Storbritannia i September 2006, hvor den ble tildelt en pris for beste PhD-paper.

BEGREPER

Gjenbruk
Nyttiggjøring av materialer og andre restprodukter ved ombruk eller materialgjenvinning.

Ombruk
Ny utnyttelse av et produkt i sin opprinnelige form.

Materialgjenvinning
Utnyttelse av avfall slik at materialet beholdes helt eller delvis.
Ved direkte materialgjenvinning brukes materialet som råstoff for tilsvarende produkter. Ved indirekte materialgjenvinning omdannes avfallet til andre typer produkter.[11]

Funksjonell levetid
Bruksmessig livstid for en komponent eller bygning. Kan begrenses av tekniske, økonomiske eller estetiske årsaker.

Teknisk levetid
Livstid knyttet til teknisk holdbarhet for en komponent eller bygning.

Miljømessig forsvarlig levetid
Den levetiden som forsvarer miljøbelastningen til et materiale.

Feriehus i Italia. Materialtilpasset livsløpsdesign? Inspirert av anonym-arkitektur verden over, kan man se for seg en byggeskikk der målet for materialbruken er å anvende rett komponent på rett sted til rett tid og på riktig måte.
Holiday home in Italy. Is this design with the material life-cycle in mind? Inspired by anonymous buildings across the world, one could imagine a way of building where the aim of the use of materials is to use the right component, at the right time, in the right way.
FOTO: CARL B. HARBITZ

ANNE SIGRID NORDBY ER ARKITEKT OG ARBEIDER MED EN DOKTORGRADSAVHANDLING VED NTNU, INSTITUTT FOR BYGGEKUNST, HISTORIE OG TEKNOLOGI, MED TEMAET «DESIGN FOR GJENBRUK AV BYGGEMATERIALER». VEILEDERE OG MEDFORFATTERE ER PROFESSOR ANNE GRETE HESTNES, NTNU OG ARKITEKT BJØRN BERGE, GAIA LISTA. PROSJEKTET ER STØTTET AV RIKSANTIKVAREN.

LIFETIME AND DEMOUNTABILITY OF BUILDING MATERIALS

By Anne Sigrid Nordby, Anne Grete Hestnes, Bjørn Berge

Abstract
The scope of this article is to discuss the environmental rationale for demountable design as one of the measures for achieving a better material resource management within the building trade. Design for Disassembly (DfD) implies optimization of construction methods and connections between components and is viewed as a strategy to facilitate maintainability, adaptability, and end-of-life material salvage (Berge 1996, Fletcher 2001, Thormark 2001, Sassi 2002, Crowther 2003). For the considerations of the practical application of DfD, scenario based predictions are viewed as a prerequisite (Brand 1994, Durmisevic 2003). As a supplement to scenario-predictions, a second mindset is presented. The assessment of a construction's need for flexibility is suggested to mirror both the knowledge that different building materials charge the environment with a certain amount of impact generated through extraction and production, and also the fact that most building types are exposed to increasing turnover rates. The underlying assumption is that high impact materials may be justified by a long lifetime, however they should be prepared for probable alterations. An analysis on environmental load of 10 wall constructions serves as a support for introducing the concept of environmentally justifiable lifetime. The comparative results reveal large differences in impact between the construction materials, and subsequently large differences in the need for demountable design. The goal is to establish an understanding of the relationship between building materials' embodied environmental load and their technical lifetime, and through this reason for a material specific need for DfD.

Anne Sigrid Nordby

This article has been published in the Proceedings of the *Global Built Environment: Towards an Integrated Approach for Sustainability* (M. Mourshed, editor, 2006), 8 pages. It was presented at the Global Built Environment Conference in Preston (UK) 11.–12 September 2006, where it was awarded a prize for best PhD paper.

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8.2 Tegl: god miljøprofil fordrer ombrukbarhet

På lang sikt

Tidligere epoker i arkitekturhistorien, så vel som de fleste folkelige byggetradisjoner, er basert på ulike former for ressursoptimert materialbruk og høy endringsdyktighet. I det siste århundret, og spesielt i perioden etter den andre verdenskrig, reflekterer de bygde omgivelser et endret verdisyn med mindre omtanke for de langsiktige konsekvensene av valg som gjøres i prosjektering og byggefase. Det viser seg at denne tankegang og praksis får betydelige miljømessige konsekvenser.

Krav om avfallssortering, utvikling av gjenvinningsordninger og innføring av restriksjoner for deponi har de siste årene bidratt til en økning i den prosentvise gjenvinningsgraden for bygg og anleggs-avfall (Landet 2007). Dette er positive utviklingstrekk og vitner om muligheter for endring i bransjen. Like fullt gjenstår problemet med en bygningsmasse som i stor grad gjenspeiler en ”lineær” bruk-og-kast holdning: Laminerte komponenter, tekniske installasjoner integrert i bærekonstruksjoner og bruk av mer enn 100 000 ulike byggematerialer inkludert en rekke tilsetningsstoffer, er faktorer som forvansker ombruk og gjenvinning. En samtidig trend er at bygninger blir utsatt for stadig raskere omløpshastighet. Resultat av disse to gjensidig forsterkende tendensene kjenner vi i form av øket press på nye råvarer og store avfallsmengder.

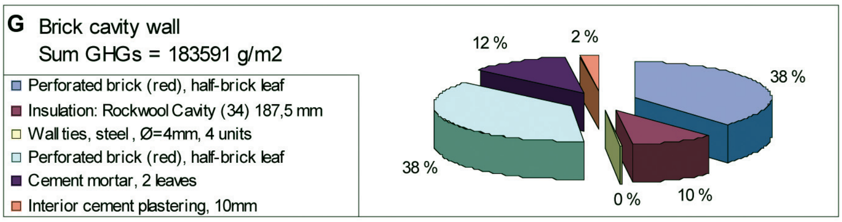
Fra et filosofisk ståsted kan man si at måten vi bygger på avslører natursynet i et samfunn. Og på mange måter stemmer dagens byggeutførelser godt overens med samtidens rådende grunnholdninger, også manifistert i turbo-kapitalisme, kjøpefest og rovdrift på naturressurser. Framtidens arkeologer vil nok klø seg i hodet og konkludere med at her, i denne utviklingsperioden (med et for øvrig høyt informasjon- og kunnskaps-nivå), ble materialene brukt på en oppsiktsvekkende lite gjennomtenkt måte. Dette vil stå i kontrast til tidligere kulturlag i utgravingsfeltet, der de kanskje vil påpeke at ressursbruken i større grad ble begrenset av småskala-økonomi, stabil demografi og/ eller temmet gjennom religiøse forordninger. Ironisk nok, ettersom våre bygde omgivelser representerer det fremste, mest kostbare og mest langlivete av kulturens uttrykksformer, er det også her vi finner de mest slående symbolene på ødsling med ressurser.

Politisk opplever vi i dag en sterk allmenn konsensus om at miljøsatsing er viktig, og at - ikke minst - utslipp av klimagasser må reguleres.

I byggebransjen har vi forskrifter som sikter mot minimering av energibruk og mot reduksjon av deponert avfall. I tillegg til dette kan miljøhensyn reflekteres i materialvalg og i byggemetoder som støtter ombruk og gjenvinning. Da arkitektur innehar et potensial for å uttrykke prioriteringer og ambisjoner på vegne av et samfunn, kan utformingen av våre fysiske omgivelser - både direkte og i en mer symbolsk betydning - brukes aktivt som en drivkraft mot en mer bærekraftig framtid.

MILJØMESSIG FORSVARLIG LEVETID

Miljøbelastningen knyttet til produksjon av tegl innebærer i første rekke et høyt energiforbruk med dertil hørende CO2-utslipp. Klimabelastningen for en 1/2 steins forblendingsvegg på en isolert trekonstruksjon er i en studie (Nordby 2006) anslått til nesten 100 kg CO_2-ekvivalenter per m^2 veggflate. Dette er utslipp beregnet for utvinning, produksjon og transport av byggematerialer og tilsvarer dermed en "dag 0"-situasjon for bygningen. Sammenlignet med en komplett yttervegg i trestenderverk, representerer dette en fem ganger så høy belastning. En isolert skallmursvegg med to 1/2 steins vanger står videre for en ca. 10 ganger så høy klimabelastning som en trestenderverksvegg. Med andre ord får vi en produksjonsmessig betydelig høyere miljøbelastning når vi bygger et teglhus sammenlignet med et hus i tre.



Klimabelastning fordelt på materialsjikt i 1 m^2 dobbeltvanget yttervegg i tegl, isolert med steinull. (Figur hentet fra Nordby 2006)

Når det gjelder tilgang på råmaterialer, er leire et rikelig forekommende materiale. Dessverre er imidlertid tegl-industrien i Norge sterkt sentralisert, og tegl kan dermed ikke lenger regnes som en lokal vare. På begynnelsen av 1900-tallet hadde vi ca 200 teglverk som var fylkesvis godt spredt rundt i landet. Disse er i dag redusert til kun ett. (www.wienerberger.no 2007) Mange tegl-produkter importeres også fra utlandet, og dette har medført en dramatisk økning av behov for transport. Da tegl er et tungt materiale å transportere, slår denne sentraliseringen svært uheldig ut i klimaregnskapet.

Det er imidlertid først når vi betrakter hele livssyklusen at det er mulig å sammenligne de totale miljøbelastningene, og for så vidt også de økonomiske kostnadene, for ett byggemateriale med ett annet. Logikken om *miljømessig forsvarlig levetid* tilsier at et materiales miljø-belastninger bør kunne gjenspeiles i en tilsvarende lang holdbarhet, slik at den opprinnelige innsatsen av energi og andre miljømessige ”investeringer” tilbakebetales gjennom komponentens brukbarhet over tid. Og nettopp når det gjelder vedlikeholdsbehov og teknisk levetid kommer tegl svært godt ut. Mer enn tusen år gamle byggverk i tegl, som f. eks den kinesiske mur, er vakre den dag i dag, og når det velges materiale til en hærverks-utsatt ungdomsskole, kan tegl være førstevalget. Når vi vet at tegl kan overleve generasjoner uten nevneverdige vedlikeholdskostnader, får den opprinnelige miljømessige belastningen en lang ”nedbetalingstid”.

Også på andre måter kan tegl forsvare energi-innsatsen under produksjon. Ferdig brent tegl er et rent materiale som bidrar til et godt innemiljø, og som gjennom sin varmelagrende evne kan redusere bygningers energibehov. I et livssyklus-perspektiv kan derfor tegl oppnå en god klimaprofil og beskrives som et miljømessig godt materiale.

Yttervegg av naturstein og tegl som gjenspeiler bruksmessige endringer. Erkebispegården i Trondheim; vestfløy oppført 1300-1753, senest restaurert i 2005. (Foto: A. S. Nordby)

GJENBRUKBARHET

Nå er det lite sannsynlig at en bygning vil bestå i samme form over hundrevis av år. Selv om det er vanskelig å spå om framtiden, vet vi at bygningsmessige endringer, riving og nybygging pga skiftende funksjonelle og tekniske behov erfaringsmessig vil inntreffe. Endringer bør derfor kunne imøtekommes i hele den tekniske levetiden til komponentene. Strategiene for endringsdyktighet; generalitet, fleksibilitet og elastisitet bør gjøres gjeldende for prosjektering av nye bygninger slik at ombygninger for ny bruk forenkles. Samtidig bør også komponentene tilrettelegges for gjenbruk.

I det tradisjonelle teglbyggeriet var ombruk og gjenvinning tatt høyde for idet svake mørteltyper gjorde det mulig å plukke ned en vegg uten å skade komponentene. Denne praksisen har vært en selvfølge i teglbyggende kulturer verden over, og antageligvis er det ingen periode i arkitekturhistorien der man ikke kan påvise at gjenbruk har funnet sted. Generelt var ombruk av tegl muliggjort så lenge ren kalkmørtel var i vanlig bruk, noe som i Europa varte fram til 1920-årene. Tradisjonelle byggemetoder i andre materialer, som for eksempel laft, var også i høy grad forberedt for ombruk, både av hele bygninger og av enkelt-elementer. Prinsippene ble imidlertid ikke overført til moderne byggeindustri, og spesielt etterkrigsarkitekturen skiller seg ut med lav gjenbrukbarhet. De ulike sementmørtlene som etter hvert kom i vanlig bruk var sterkere enn teglet i seg selv, og forvansket senere ombruk.

Derfor er gjenbruk av tegl i dag først og fremst forbundet med materialgjenvinning i form av knusing, sammen med betong og annet murmateriale, til bruk i fyllinger. Dette kalles på engelsk *downcycling*, og impliserer et miljømessig sett dårligere alternativ fordi gjenvinningsprosessen forbruker ytterligere energi mens produktet reduseres til et materiale med lavere bruksverdi enn det opprinnelige. Hvis vi i fremtiden skal ivareta god ressursbruk i prosjektering av bygninger, må gjenbrukbarhet på nytt inn som et design-kriterium, ikke minst når man skal forsvare en høy miljø-investering i produksjon av byggematerialer. En ambisjon burde derfor være å tilrettelegge produksjon og oppføring av teglkonstruksjoner på en slik måte at ombruk stimuleres. For at dette skal bli mulig, må endringer i overordnet tankegang finne sted.

BEGREPER

Gjenbruk:
Nyttiggjøring av komponenter og materialer ved ombruk eller materialgjenvinning.
Ombruk:
Ny utnyttelse av et produkt i sin opprinnelige form.
Materialgjenvinning:
Prosessering og ny utnyttelse av avfallsmaterialer i nye produkter.
Funksjonell levetid:
Forventet eller faktisk bruksmessig levetid for et komponent eller en bygning, kan begrenses av tekniske, økonomiske eller estetiske årsaker.
Teknisk levetid:
Levetid knyttet til teknisk holdbarhet for en komponent eller bygning.

Kriterier; utfordringer og muligheter

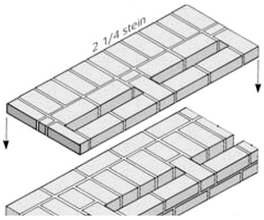
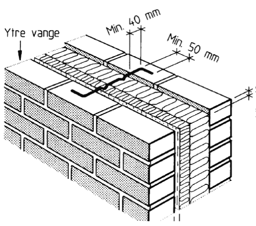
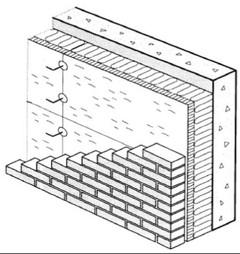
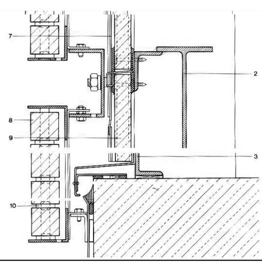
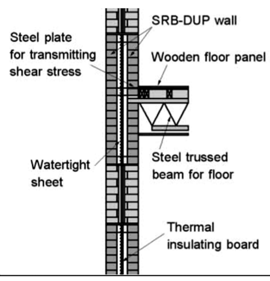
I dette essayet drøftes praktiske og tekniske utfordringer, men også arkitektoniske potensialer for ombrukbare teglkonstruksjoner. I diskusjonen anvendes teori fra tidligere studier (Nordby 2007), der kriteriene for gjenbrukbarhet er definert. Kriteriet *reversible forbindelser*, som kan

St. Olavs universitets-sykehus 2005: Hudavdelingen fra 1800-tallet rives for å gi plass til nye sykehusbygninger, og prosjektet oppnår høy grad av lokal materialgjenvinning gjennom knusing av masser. (Foto: R. Bohne)

Noe av dette teglet ble også renset for direkte ombruk gjennom arbeidsforetaket Stavne Gård. Bildet viser ombrukt tegl i en skulptur i den nye sykehusparken i 2007. Imidlertid: Bruk av sementmørtel tillater ikke ombruk flere ganger, og setter dermed en stopper for denne muligheten for senere generasjoner (Foto: A. S. Nordby).

oppnås gjennom bruk av svak mørtel, er et viktig moment, men utgjør bare en av flere anbefalinger for å oppnå gjenbrukbarhet. Hvert av de seks kriteriene sammenfatter ett sett designstrategier samlet fra forskning innen både bygningsteknologi og industridesign (Crowther 2003), og danner samtidig overskrifter for drøftingen. En overbyggende hypotese er at kravet om gjenbrukbarhet i byggeriet kan ses ikke bare som enda et instrumentelt reglement for miljø-effektivitet, men som en positiv drivkraft for å skape meningsfull arkitektur.

Fem ulike yttervegger i tegl er beskrevet for å illustrere typiske utviklingstrekk relatert til ombrukbarhet for teglkonstruksjoner. Som et eksempel på historisk murverk er valgt Trondheimshulmur, en 2 1/4 steins vegg murt med kalkmørtel. To alminnelig brukte konstruksjoner med mer oppdatert isolasjonsstandard og bruk av sementmørtel (hulmur og forblendingsvegg) er plukket fra anbefalte byggdetaljer. Til slutt er to mørtelfrie varianter hentet fra senere konkrete prosjekter: I tilbygget til ”IRCAM”-bygningen i Paris fra 1989 (av R. Piano) er hulltegl montert med stålstag i aluminiumsrammer i en utvendig kledning (beskrevet i Dahl 1992), mens et eksperimentelt byggeri i Japan bruker forspent tørrmur med stålplater og bolter for hvert skift (”SRB-DUP”, beskrevet i Yamaguchi 2007) som en isolert yttervegg.

	**1. Trondhjemshulmur,** historisk murverk • Fasadetegl, 1 ½ steins vange, kalkmørtel • Luftspalte, ¼ steins dybde • Bindere av stein • Lavbrent stein, ½ steins vange, kalkmørtel • Innvendig puss
	**2. Hulmur i tegl,** isolert • Fasadetegl, ½ steins vange, sementmørtel • Luftspalte • Bindere av stål • Isolasjon: Rockwool Mur, 50 mm + Rockwool A, 125 mm • ½ steins vange, sementmørtel • Innvendig puss
	**3. Forblendingsvegg i tegl,** isolert • Fasadetegl, ½ steins vange, sementmørtel • Luftspalte • Bindere av stål + avstandsholdere • Isolasjon: Rockwool Mur, 50 mm + Rockwool A, 125 mm • 150 mm betong, plasstøpt
	**4. IRCAM-bygning;** fleksibelt fasadesystem • 275x50x50 mm perforert tegl • Avstandsholdere i nylon • Aluminiumsramme, 60/70 mm vinkel • Bolter, avstandsholdere i teflon • Aluminiumsprofil, 120/60 mm • Korrugert stålplate-kledning • Armert betong prefab vegg • Stålprofil HEA 180 og IPE 120
	**5. SRB-DUP;** forspent "tørrmur" • Fasadetegl, ½ steins vange, SRB-DUP system med stålplater og bolter • Luftspalte • Isolasjonsplate • ½ steins teglvange, SRB-DUP system

Eksempler på ulike teglkonstruksjoner som representerer utviklingstrekk knyttet til ombrukbarhet. Figurene er hentet fra:
1. Byggdetaljblad 723.308; Eldre yttervegger av mur og betong. Metoder og materialer (SINTEF Byggforsk)
2. Byggdetaljblad 523.231; Skallmurvegg med vanger av murstein og murblokker (SINTEF Byggforsk)
3. Byggdetaljblad 542.301; Murt forblending (SINTEF Byggforsk)
4. DETAIL, Review of Architecture + Construction Details, 1990/4, S. 396.
5. Yamaguchi, K. et al. (2007) A new structural system: friction-resistant dry-masonry. Building Research and Information 35 (6), pp. 616-628

BEGRENSET MATERIALVALG

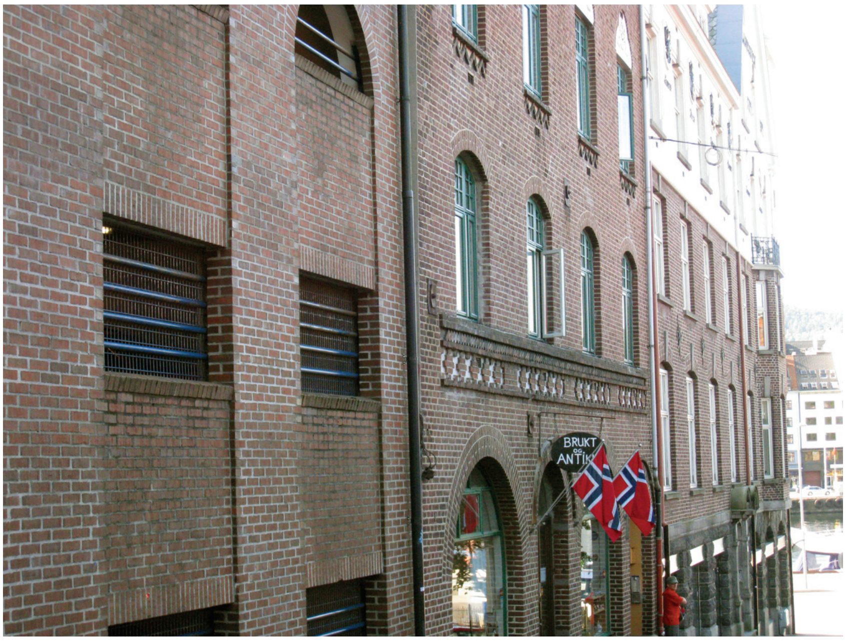
- Begrens antall materialtyper, bruk helst monomaterial-komponenter
- Begrens totalt antall og ulike typer komponenter og forbindelsesmidler
- Unngå farlige og giftige stoffer og overflatebehandlinger

Ifølge det første kriteriet for gjenbrukbarhet, er det gunstig å begrense materialvalget. Enkelhet i material-sammensetningen for hver komponent, og også totalt for bygningen, gir flere fordeler i prosessene rundt riving, sortering og etterbruk. Tegl består av tørket og brent leire og kan i seg selv regnes som et monomateriale til tross for noe tilsetningsstoffer. Monomateriale betyr at komponentet er bygget opp av et homogent materiale tvers igjennom (Berge 2000). Mange byggeprodukter er i dag satt sammen av permanent sammenføyde deler eller lag, der lagene kan bestå av materialer med ulik levetid. Dette fører til dårlig ressursbruk fordi hvis bare ett lag er slitt, må hele komponentet kasseres. Bruk av monomaterialer muliggjør også nødvendig kvalitetskontroll av komponentene før eventuell ombruk.

Videre trenger ikke tegl overflatebehandling, noe som også er en fordel med tanke på ombruk. Materialet beholdes da rent både i hel og knust form, og det utsettes ikke for forurensninger i form av blanding av materialtyper. Ferdig brent tegl inneholder heller ikke miljøgifter som evt. kunne forvansket en ombruks/ gjenvinnings-prosess.

Tegl kan fungere både bærende og som innvendig/ utvendig kledning. Dette gir muligheter for konstruksjoner med totalt sett få materialtyper, og dermed har man ved selektiv riving også færre fraksjoner. Dette gjør sorteringsjobben enklere, og i tillegg er det plassbesparende. Mange byggeplasser i urbane strøk har problemer med å finne plass til alle containere som er nødvendig for avfallsbehandling under bygging, og enklere er det ikke nødvendigvis ved riving. Et annet poeng er at mengden av hvert materiale da blir relativt større, og dermed har man en bedre mulighet for avsetning i markedet. Før var det generelt en mer desentralisert byggevare-industri. Da var det i større grad de lokale materialressursene som la grunnlaget for en felles byggeskikk i regionen, og dette kunne også gi fordeler for ombruk. I en situasjon der man har færre materialtyper å velge i, vil markedet for ombrukte materialer i større grad tilsvare markedet for nye produkter, og ombruk kan enklere innpasses i nytt byggeri.

Forbindelses-middelet for tegl er vanligvis mørtel. På den ene siden er det fordelaktig med bare én type forbindelsesmiddel, på den andre siden skaper mørtelen problemer ved riving fordi den er bundet kjemisk til teglsteinene. Idet teglsteinen legges i mørtel blir det derfor vanskeligere å snakke om tegl som et monomateriale. Imidlertid er sammensetningen av mørtelen utslagsgivende for gjenbrukbarheten. Dette punktet blir videre drøftet under *reversible forbindelser.*



Arkitektur fra ulike epoker veves sammen gjennom et felles materialvalg i Bergen. (foto: A. S. Nordby)

Et begrenset materialvalg resulterer i en homogen arkitektur, uavhengig av stiler og tidsepoker, og ulike kulturlag i en bebyggelse veves sammen. Lokale materialer går ofte også i ett med sine naturlige omgivelser, og er en av grunnene til at opprinnelig byggeskikk beundres verden over. Begrenset materialvalg kan videre skape et grunnlag for formgivingsmessig enkelhet og minimalisme, en velkjent holdning i den modernistiske tradisjonen.

Gjennom begrenset materialbruk kan en bygnings arkitektoniske uttrykk forsterkes og raffineres. Materialmessig enkelhet sporer til undersøkelser av de utvalgte materialenes egenskaper, noe som kan gi innsikt i ulike tekniske og miljømessige kvaliteter. Idet denne kunnskapen omsettes i praksis, kan en bærekraftig kultivering av byggekomponenter finne sted.

LANG HOLDBARHET

- Formgi holdbare komponenter som kan tåle gjentatt bruk og vare i flere bygnings-generasjoner
- Vær spesielt oppmerksom på knutepunkter og forbindelsesledd, og sørg for hensiktsmessige toleranser for gjentatt demontering og remontering
- Formgi komponenter med arkitektonisk kvalitet

Som tidligere beskrevet skårer tegl høyt på teknisk levetid, og forsvarer dermed i høy grad miljø-innsatsen under fremstilling. Stein av god kvalitet varer lenge, og tåler også gjentatt ombruk. Imidlertid, når det gjelder teglkvalitet kommer vi inn på et dilemma; ettersom ekstrem bestandighet og frostsikkerhet har blitt normen, blir all norsk tegl brent ved høye temperaturer. Selv om fasader som er beskyttet med puss og innvendige vegger ikke trenger denne høye kvaliteten, tilbys kun hardbrent tegl i Norge i dag.

Det viser seg at man kan oppnå en rekke miljømessige fordeler gjennom differensiering av kvalitet gjennom ulik brenningsgrad. Innvendig vange i en skallmur trenger ikke være brent til sintring (1000 grader) som er vanlig for konvensjonell teglstein. 400-600 grader vil være nok, og dermed kan energiforbruket reduseres drastisk. Da bruksområdene til tegl varierer, vil et større utvalg tegltyper med ulik brenningsgrad også kunne innfri andre og nye krav, f.eks til fuktregulering. I lavbrent stein beholder teglmaterialet en mer åpen porestruktur som kan oppta og avgi fuktighet i rommet. Dette er ikke minst et viktig poeng i rom med store svingninger i damptrykk. Man kan også benytte ubrent stein i innvendige vanger og vegger da disse har meget gode fuktregulerende egenskaper. Samtidig med at man får et mindre energiforbruk til brenning ved lavere temperaturer, har ubrent eller lavbrent leire den fordelen at materialet etter funksjonell levetid lettere kan materialgjenvinnes. Et hovedpoeng må være å få til en ressursutnyttelse som tar hensyn til den opprinnelige miljømessige investeringen.

Når det gjelder den arkitektoniske helheten, kan det også knyttes noen kommentarer til lang holdbarhet. I utgangspunktet utfordrer en prosessorientert byggeskikk det populære synet på arkitektur. Tidsskrifter og publikasjoner har en tendens til å dyrke design som et sceneografisk uttrykk der originalitet og tidsriktighet er viktige faktorer. Arkitektur reduseres gjennom dette til en formalistisk henvisning av ideer framfor å diskuteres som tektonisk gestaltet byggeri. Ønsket om en tidsriktig arkitektur medfører i mange tilfeller at bygninger blir sårbare ovenfor raske motesvingninger, og slik kan den funksjonelle levetiden til materialer bli sterkt redusert. I den offentlige debatten om byutvikling spisses problemstillingen rundt behovet for merkevarebygging gjennom enkeltstående "signalbygg", som representerer et individ-fokusert og markedsliberalistisk syn framfor å fremme helhet og sammenheng.

Dette arkitektursynet passer dårlig med livssyklus-tenkning og kriterier for gjenbrukbarhet. Prototypene for fleksibelt design er snarere å finne i tradisjonell byggeskikk, og består av bygningsmessige *mønstre*. Steward Brand (Brand 1994), teoretiker og talsmann for livssyklusdesign, anbefaler å starte konservativt, med respekt for regionale tradisjoner og eksisterende urbane strukturer. Gjennom studier av omgivelsenes "spilleregler", kan arkitekter erfare at det ikke alltid er behov for å tilføre så mye nytt. Gjennom bruk vil isteden de enkelte bygningers særegenheter tre fram.

Hvis man kobler lang holdbarhet i form av teknisk og arkitektonisk kvalitet med livssyklus-perspektiv og gjenbrukbarhet, sparer man ikke bare produksjons-belastninger for nye materialer, men også miljøbelastninger knyttet til transport og til deponi av avfall. Idet fysiske omgivelser og byggekomponenter fremstilles med kløkt, omtanke og formgivingsglede, vil de også kunne få en affeksjonsverdi for brukerne. Dermed blir sjansene store for at både bygninger og materialer vedlikeholdes og ombrukes slik at man oppnår en forsvarlig ressursbruk. Tegl er et eksempel på et materiale som passer godt inn i denne filosofien.

HØY GENERALITET

- Bruk standard dimensjoner, modulære konstruksjoner og et standard grid-system
- Bruk komponenter med små dimensjoner og lett vekt
- Reduser kompleksiteten til komponenter og konstruksjoner, og planlegg for bruk av vanlig verktøy og utstyr

Generalitet er et begrep som kan anvendes både for bygninger i sin helhet og for komponenter. En bygning med høy generalitet har muligheter for endring av bruk innenfor eksisterende planløsning og romhøyde. Bygårder bygget før funksjonalismen har i større grad generelle rom med liknende form og størrelse. Disse har vist seg levedyktige på grunn av sin endringsdyktighet som gjør at de kan bygges om i takt med beboernes behov (Leland 2006, Manum 2006).

For at byggematerialer skal være interessante for ombruk, må komponentene være generelt utformet slik at man beholder en fleksibilitet i forhold til ny bruk. Dette fører til at komponentene kan inngå i ulike arkitektoniske sammenhenger både når det gjelder konstruksjonstyper,

Teglstein er små, "molekylære" byggeklosser som er fleksible i forhold til varierende konstruksjonsmessige behov og arkitektoniske uttrykk. Hvelv i krypten under Colonia Güell, Catalonia. Ark: A. Gaudi 1898 (Foto:Jan Siem) stil og detaljering. Feilslått politikk eller spekulasjoner kan føre til overskudd av bygninger med en bestemt funksjon som ofte ikke lar seg omforme til andre formål. Likeledes kan, som nevnt, motesvingninger medvirke til at design utdateres. Hvis da bygningene skal rives og materialene ombrukes, må utformingen av de nye bygningene ikke være forhåndsbestemt. Det blir den hvis komponentene er for store eller for spesielle, slik vi dessverre ofte ser i dagens prefabrikkerte bygninger. Case 4: IRCAM-bygningen er et eksempel på bruk av spesielle komponenter som ikke uten videre lar seg ombruke i en ny sammenheng.

Den tradisjonelle teglsteinen kan ses som en *"molekylær"* byggekloss som på mange måter er optimalt utformet for å gi arkitektonisk fleksibilitet: Vekt og mål gir rike muligheter til å løse funksjonelle og strukturelle utfordringer. Et relativt lite format er utgangspunktet. Videre gjør de ulike side-dimensjoner for flask, kant og løpeside, i tillegg til justeringsmuligheter i mørtelfugen, at steinen kan tilpasses ulike konstruktive krav og at detaljeringen i stor grad kan varieres. Konstruktive prinsipper omfatter søyler, buer og hvelv i mange varianter, og stil-epoker så ulike som den klassiske og den funksjonalistiske har oppvist totalt forskjellige arkitektoniske uttrykk i tegl.

Det lille formatet er også egnet for selvbygging, noe som antas å fremme lokalt ombruk. Relativt enkle verktøy og metoder gjør at mindre byggeoppgaver ikke blir uoverkommelige for en ufaglært. Dermed blir ombruk av tegl aktualisert ikke bare gjennom industrien, men også i det private markedet.

REVERSIBLE FORBINDELSER

- Bruk reversible forbindelser for komponentdeler, mellom komponenter og mellom bygningsdeler
- Tilrettelegg for parallell demontering og remontering

En forutsetning for en ombrukbar konstruksjon er at knutepunktene utføres som reversible forbindelser. Mekaniske fester foretrekkes framfor kjemisk binding. Da mørtel i utgangspunktet fester seg kjemisk til teglsteinene, er dette punktet problematisk i dagens mest brukte teglkonstruksjoner. Rensing før ombruk er påkrevet og kan være en tidkrevende og arbeidsutsatt prosess. Styrken i bindingen er imidlertid avhengig av mørteltype.

Norsk murverk bygget før 1925 er vanligvis murt med ren kalkmørtel som er svak og gir mulighet for demontering uten å skade teglsteinene (jmf case 1: Trondheimshulmur). Rensing av tegl murt med ren kalkmørtel er relativt ukomplisert. Murverk fra perioden mellom 1925 og 1955 kan også være demonterbart selv om små mengder sement ble tilsatt kalken. De ulike sementbaserte mørtel-blandingene som ble introdusert etter 1955 derimot, er vanligvis sterkere enn selve teglet, og ved riving vil derfor steinen ødelegges før mørtelen. Teglkonstruksjoner bygget etter 1955 regnes derfor som ikke gjenbrukbare (Madsø 2001). Da kalkmørtel er brukt i historiske bygninger, er kunnskapen om bruk av kalk i dag først og fremst knyttet til restaurering. Imidlertid viser det seg at kalk, i tillegg til å gi demonterbare konstruksjoner, kan oppvise en rekke andre tekniske og miljømessige fordeler. Kalk er mer fleksibel og mer hygroskopisk enn sement, og man kan prosjektere vegger uten ekspansjonsfuger. I tillegg er den smidig å mure med, og fersk mørtel kan holde seg fra en dag til den neste. Tegl og kalkmørtel utgjør dessuten en materialmessig mer homogen vegg, som blir mindre utsatt for frostsprengning. På dette grunnlaget vurderes kalk nå på nytt som bindemiddel i murverk.

Noen utfordringer ved bruk av kalkmørtler bør bemerkes, og et kritisk punkt er herdetiden. Kalk krever mer tid enn sement for å herde og for å oppnå full styrke, noe som kan gå ut over bygge-effektiviteten. Man må dessuten unngå frost før herding, og dette forutsetter bygging tidlig i sommersesongen. En annen begrensning knytter seg til motstandsevne ovenfor sideveiskrefter, både under bygging og i bruk. Da historisk kalkmurverk var avhengig av en viss masse for å gi stabilitet, kan bygging av en halv steins vange med kalk etter samme prinsipper som for sementmørtel bli problematisk (Yates 2007). Man bør derfor være oppmerksom på disse utfordringene både ved prosjektering og under bygging. Kalkbaserte mørtler inkluderer en rekke produkter med varierende egenskaper i forhold til herdetid og styrke. Mer informasjon om kalkbaserte mørtler finnes på f.eks www.scotlime.org/trad_lime.html.

En annen mulighet er å bruke tegl som "tørrmures" og dermed skape murverk helt uavhengig av mørtel. Eksempler på dette ses i vegg 4 og 5: Pianos IRCAM-bygning i Paris og forsøksbyggeri med SRB-DUP systemet i Japan. Den første bygningen har en demonterbar fasade med

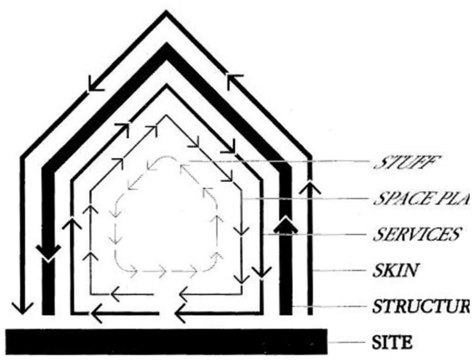
Demonterbart fasadesystem av tegl med aluminiumsrammer og bolter i tilbygget til IRCAM-bygningen, Paris. Arkitekt: R. Piano 1988 (foto: Jan Siem) perforerte teglstein innfelt i aluminiumskassetter. Dette forenkler utskifting når ett eller flere komponenter er slitt. Kanskje er denne ytterhuden ikke tett nok for et norsk vestlands-klima. Imidlertid kan man se for seg liknende prinsipper brukt andre steder i bygningen, for eksempel i innervanger. Det andre eksempelet bruker en forspent tørrmur, der stålplater og bolter for hvert skift holder teglsteinene sammen. Systemet gir en sterk murvange spesielt rustet til å oppta skjærkrefter i en jordskjelvsutsatt del av verden. For norske seismiske forhold er muligens veggens styrke overdreven, men uansett gir dette prinsippet en demonterbar murvange, der teglsteinene kan skrues ut og ombrukes.

FORNUFTIG LAGDELING

- Formgi de ulike sjiktene i bygningen som konstruktivt uavhengige systemer
- Arranger sjiktene i forhold til forventet funksjonell og teknisk levetid for komponentene

Et mye omtalt prinsipp i livssyklus-prosjektering er behovet for lagdelte konstruksjoner. Teorien tar utgangspunkt i at ulike lag eller sjikt i en bygning endres i ulik takt. Derfor må en endringsdyktig bygning tillate friksjonsfrihet mellom de ulike systemene (Brand 1994). Når hvert sjikt er konstruktivt uavhengig og hver komponent utskiftbar, kan man imøtegå problemet med en ofte lang teknisk levetid for komponenter og et ofte kortere funksjonell levetid for et sjikt eller en bygning. Dette har klare fordeler i et vedlikeholdsperspektiv. På den annen side kan det diskuteres om lagdeling bør være et mål i seg selv.

Historisk har bygningers ytterhud utviklet seg fra å være integrerte, hvor alle bygningstekniske funksjoner ivaretas i ett gjennomgående materiale, til differensierte, hvor ulike sjikt løser hver sin oppgave. En moderne yttervegg har gjerne en rekke type komponenter som tar hånd om ulike konstruktive og klimaregulerende funksjoner. Denne kompleksiteten speiler industrialismens tankegang; å effektivisere produk-



Prinsippet om lagdeling: ulike sjikt i en bygning endres i ulik takt. (Etter Stewart Brand 1994) sjonsprosessene gjennom arbeidsdeling. Vi har også fått nye og skjerpede krav til hva veggen skal utføre, og i de siste årene har fokus ikke minst vært på høye krav til varmeisolering. Denne utviklingen har imidlertid også ført til mer komplekse og materialforbrukende konstruksjoner. Yttervegg og tak kan bli prosjekteringstunge øvelser idet en lang rekke sammenføyningsdetaljer skal løses både byggeteknisk og estetisk, og situasjonen medfører en sårbarhet fordi det er mange punkter der gjennomføringen kan svikte, i prosjekteringen så vel som i utførelsesfasen (Selmer 2003).

Når det gjelder yttervegger i tegl, har kravet om økt isolasjonsstandard ført til en oppsplitting av det tidligere integrerte murverket. Denne oppsplittingen har fått konsekvenser av både teknisk og arkitektonisk art. Håndverksmessig er det ikke lenger noen sammenheng mellom ytterhud og bæring, og fasaden formidler ikke lenger bygningens bakenforliggende konstruksjoner (Dahl 1992). Som en konsekvens av denne differensieringen blir det bærende sjiktet ofte skiftet ut med mer rasjonelle bæresystemer i tre, stål eller betong (Jmf. case 3).

Gjenbrukbarhet kan oppnås for både integrerte og differensierte konstruksjoner. Det viktige er at veggens lag utføres på en logisk måte. Hvis flere enn ett sjikt, bør disse være konstruktivt uavhengige og dessuten stå i riktig rekkefølge ift. levetid slik at man kan nå de lagene/ komponentene som gjerne erstattes først (Durmisevic 2006). Dette kan angå både funksjonell og teknisk levetid; noen komponenter skiftes ut pga nye tekniske krav eller ønsker om annet visuelt uttrykk, andre må erstattes fordi materialet slites. Dette dilemmaet kommer til uttrykk i isolasjonslaget i en moderne skallmur, som lett blir en akilleshæl i konstruksjonen. Sjiktet med Rockwool, brukt i case 2 og 3, kan ikke nåes for utskifting uten å rive ned teglvangene som teknisk, og kanskje også funksjonelt sett, varer mye lengre.

TILGJENGELIG INFORMASJON

- Merk materialer og komponenttyper
- Merk og tilrettelegg for tilgang til knutepunkter i konstruksjonen
- Sørg for oppdaterte "as-built" tegninger, materiallogg og demonterings-beskrivelse

I bilproduksjon og i elektronikkbransjen, der gjenvinningsordninger er implementert og delvis også lovpålagt, er merking av materialer og komponenter en viktig strategi i tilretteleggingen for gjenbruk. I en ombrukssituasjon for byggevarer kunne det også være fordel om produktinformasjon var festet/ trykket direkte på komponentene slik at ulike materialtyper og kvaliteter enkelt kan sorteres etter første generasjons bruk. Navn på produsent, angivelse av råvare og kvalitet samt sted og dato er kunnskap om komponenten som kan videreføres til kommende generasjoner, og bli et viktig vurderingskriterium for mulig videre bruk. Andre kilder for informasjon om bygninger som for eksempel ”as built” tegninger og materiallogg er også verdifulle for ettertiden, og bør oppdateres i forbindelse med ombygginger og renovering. Imidlertid er overføring av informasjon gjennom disse kildene avhengig av utbyggers ambisjonsnivå og videre generasjoners vedlikeholdsevne, noe som på ingen måte kan garanteres av produsent. Spesielt i en situasjon der vi har en større differensiering av materialkvaliteter enn i dag, blir merking et viktig moment. Sortering i for eksempel høybrent/ lavbrent tegl i en dobbeltvanget yttervegg blir da en overkommelig oppgave etter at mørtelen er fjernet.

Det var kanskje romerne som startet skikken med preging av tegl, og som dermed gjorde det mer interessant å være arkeolog i ettertid. Over tusen år senere kunne informasjon om produksjonsforhold, transport og økonomi i romertiden avleses og kartlegges. Da tegl presses i former, burde ikke merkingen gi noen større utfordringer for produksjonen også i dag. Symboler kan standardiseres innen industrien slik at et enkelt kodespråk egnet for pressing i leire kan utvikles. I tillegg til de rent tekniske fordelene, kan man se for seg at innprenting av informasjon om kvalitet osv. kan medvirke til å gi en dekorativ effekt. Teglsteinen kan formes slik at den siden av steinen (eller de sidene) som inneholder informasjon gir en merverdi i form av struktur/ relieff som kan være med på å skape særegne arkitektoniske uttrykk. Preging kunne på denne måten gi framtidige brukere og rivings-entreprenører den nødvendige kunnskap for gjenbruk - og kanskje også et glimt av de holdninger og premisser for kultivering av materialer som rådet på byggetidspunktet.

Det arkitektoniske språket i seg selv kan også fungere som en budbringer av nyttig informasjon når det gjelder gjenbrukbarhet. Vi snakker nå om en mer underforstått kunnskap som er knyttet til lesbarheten

Gammel, preget teglstein er populære ombruks-produkter i Ungarn (foto: Klaudia Farkas)

Lesbarheten i det arkitektoniske språket gir tilgang til informasjon om komponentene som bygningene består av og deres potensialer for gjenbruk. Bindingsverks-hus i Holbæk, Danmark (foto: Finn Hakonsen) i konstruksjonene, og som man ofte finner i tradisjonell byggeskikk. Enkle konstruksjonsmetoder, integrert funksjonalitet og bruk av monomaterialer underbygger denne lesbarheten. Enkelte historiske bygningstyper, som for eksempel det europeiske bindingsverket, viser materialene fram som om de skulle være på utstilling i en byggevarehandel. Informasjon om gjenbrukspotensialet til komponentene blir dermed i høyeste grad tilgjengeliggjort til nåtidige så vel som til mulige framtidige brukere.

Endringsnøkler

UTVIKLING AV MØRTEL OG STEIN

Til tross for store endringer i teglbyggeriet i løpet av de siste hundre år, beskrives ofte byggebransjen som en konservativ og treg sektor. Idet mange aktører opptrer uavhengig av hverandre, kan den samlede aktiviteten lett bli ukoordinert. Selv om ett byggeprosjekt finner gode løsninger på sine utfordringer, får ikke dette nødvendigvis noen betydning for andre prosjekter. Imidlertid virker endringer i rammeverk og konvensjoner ”systemisk” og kan få vidtrekkende konsekvenser, på godt og vondt. Feil her kan ta generasjoner å korrigere (Kohler 2007). Dagens norske sement-baserte mørteltyper er utviklet for å lime tegl i tynne vanger og for å understøtte slanke, armerte konstruksjoner med redusert murmasse. Styrken på denne mørtelen overgår, som nevnt, i høy grad det som er ønskelig i forhold til gjenbrukbarhet.

Senere prosjekter, spesielt i England, har eksperimentert med bruk av kalkbasert mørtel i nye bygninger. Til tross for de nevnte utfordringer ved prosjektering og bygging har man oppnådd gode resultater ved bruk av kalk, også i isolerte skallmur-konstruksjoner (Beare 2008). Når man bruker kalk som bindemiddel og som puss holdes de miljømessige belastningene lave (Fossdal 2003), og som en av flere fordeler oppnås demonterbarhet. Flere nybygg med kalk i nordisk klima kunne være ønskelig for å utrede potensialet for gjeninnføring av kalkbaserte mørtler for murverk.

Ny utvikling av stein og blokker peker også på noen interessante muligheter. Brente leireprodukter som poroton og leca har bedre isolerende egenskaper enn tradisjonell tegl. Disse blokkene brukes derfor i yttervegger uten tilleggsisolajon i mange sentral- og sør-europeiske land, eventuelt i kombinasjon med tradisjonell tegl i fasaden (Leimand 2007). En annen fordel med større blokker er at de enklere kan stables, og at de er detaljerte slik at bare et minimum av mørtel er nødvendig for oppmuring. Noen har til og med et låsesystem med not og fjær som i enkelte sammenhenger gjør blokkene uavhengige av mørtel (se: http://se.maxit-cms.com/922; DSM). Dermed unngås kuldebruer i fugene, man får et homogent murverk, og samtidig forenkles gjenbruk av blokkene.

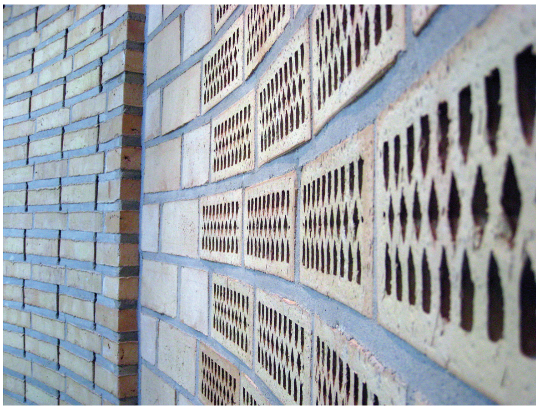
Under merkelappen ”bærekraftig murverk” viser ulike konstruksjonsmetoder en “back to basic” trend. Lavteknologiske materialtyper som jord, halm og hamp blandet med sand og kalk har lav miljøbelastning, og bruken av plantefibre bedrer isolasjons-egenskapene (se for eksempel: www.hemplime.org.uk/whatis.html). Disse materialene kan enten støpes i forskaling eller formes til blokker. I begge tilfeller framstilles en homogen og konstruktivt integrert vegg med redusert kompleksitet og arkitektonisk sammenheng som resultat. I tillegg oppnås en forenklet material-gjenvinning (Stevenson 2005).

MATERIALENES LOGIKK

Byggekomponenters materialegenskaper kan svare på ulike tekniske behov. I tillegg til konstruktiv styrke, vanntetting og varmeisolasjon, kan ytelseskrav knyttes til å skape et godt inneklima. Materialer kan brukes som aktive og operative elementer i interiører. Tunge materialers varmekapasitet kan dempe daglige temperatur-svingninger, og gjennom dette redusere energibehov til oppvarming og kjøling. Porøse materialer med evne til å regulere fuktighet kan komplimentere og i noen tilfeller erstatte ventilasjonsanlegg (Simonson 2002). Videre kan akustisk kontroll håndteres ved bruk av komponenter med overflater som modifiserer eller absorberer støy. Disse tiltakene kan integreres i arkitekturen, og logikken er basert på en helhetlig tilnærming. Selv om ulike tekniske installasjoner kan forbedre bygningers direkte yteevne, så kan de også føre til høyere kompleksitet og sårbarhet. Fokus på de fysiske og kjemiske potensialer innebygd i materialene kan isteden føre til mer robuste løsninger.

Begrepet tektonikk impliserer bruk av teknologiske parametre som en kilde for design. I utgangspunktet er begrepet brukt om bærekonstruksjoner og materialbruk der logikken i kraftoverføring eller produksjonsbetingelser danner basis for det estetiske uttrykket. Med komponenten som en minste ”molekylær” byggekloss som forener tekniske og estetiske målsetninger, kan en tektonisk holdning underbygge materialenes logikk som en premiss for arkitekturprosjektering. Tekniske egenskaper som materialkvalitet, komponentutforming og forbindelsesdetaljer kan legge føringer for konstruksjonen og, i en større sammenheng, inspirere arkitekturen. Miljømessige hensyn bør integreres i denne logikken.

Temaet *gjenbrukbarhet* gir bestemte føringer for prosjektering, og kriteriene kan i varierende grad knyttes til tektonikk. En gjenbrukbar komponent-design er basert på logiske premisser for ressursoptimering over flere hus-generasjoner, og synliggjør viktigheten av operative egenskaper ved byggekomponenter. Når denne nytteverdien løftes fram og uttrykkes i bygningens estetikk, kan den bidra til å skape meningsfull arkitektur i den forstand at miljøhensyn manifesteres i våre fysiske omgivelser. Istedenfor å diskutere hvorvidt ”grønn” arkitektur har eller bør ha en spesiell stil, kan en tektonisk holdning fungere som et mer praktisk konsept for bærekraft på komponentnivå.



Tegl brukt som akustisk regulerende element i trapperom. Realfagbygget, Gløshaugen av Narud Stokke Wiig/ Hus Arkitekter 2001 (Foto: A. S. Nordby)

Tegl brukt i baderom, enebolig Kleven/ Styrmoe, Bærum av arkitekt Knut Hjeltnes, 2003. Glasert tegl bak badekar, vokset og polert tegl i gulv og ellers ubehandlet tegl i veggen ivaretar henholdsvis fuktavvisning og dampregulering (Foto: A. S. Nordby)

ØKONOMISKE RAMMEBETINGELSER

Økonomien, som må regnes som et viktig rammeverk for hvordan vi bygger, blir ofte presentert som en hindring i det å kunne satse på endringsdyktige og gjenbrukbare konstruksjoner. Imidlertid, i et langtids-perspektiv kan bærekraftige løsninger vise seg å være de mest lønnsomme. Som Stern-rapporten peker på, krever globale miljøtrusler at man setter vide avgrensninger for økonomiske analyser, både geografisk og i tid (Stern 2006). Beslutninger i et enkelt byggeprosjekt er i dag ofte utelukkende basert på anskaffelses-kostnader, men for å kunne synliggjøre fordelene av bærekraftige løsninger må man isteden anvende et livssyklus-perspektiv. Dette vil for eksempel ha innflytelse på grad av varmeisolasjon og på valg av holdbare materialer, vedlikeholdsvennlighet og fleksibilitet. Gjennom å sette av mer tid til prosjektering og byggefase kan man unngå feil og mangler som man ellers må betale dyrt for i driftsperioden. Med disse intensjoner ble livssykluskostnader (LCC) gjort til en påbudt øvelse for offentlige anskaffelser i Norge i 2001 (MD 2007). Selv om LCC metodologien har sine begrensninger når det gjelder miljømessige, sosiale og kulturelle omkostninger, er det lov å håpe på at denne tankegangen kan hjelpe til å fokusere på bærekraftige løsninger i et langtids-perspektiv (Cole 2000).

På 1950/ 60 tallet skjedde det et skifte i kostnadsbelastning mellom materialer og arbeidstid, slik at det ikke lenger ble økonomisk lønnsomt å optimalisere materialbruken gjennom å bruke mer tid til prosjektering eller til utførelse (Noach/ Nilsen 1985/ 2008). Istedenfor å eksempelvis la ingeniøren bruke arbeidstimer på å beregne ulike tykkelser på betongdekker i henhold til ulik lastfordeling slik det var vanlig på

1920/30-tallet, la man nå heller et jevntykt dekke som tilsvarte høyeste belastning. Teglhvelv er et godt eksempel på en ressursbesparende men arbeidsintensiv konstruksjon, som ikke minst av økonomiske årsaker nå er sjeldne å se i vår del av verden. Dette skiftet fikk naturlig nok betydning for ressursbruken, men også for arkitekturen. Når man ikke lenger "møter motstand" i materialet i form av tekniske eller økonomiske hensyn, får dette også konsekvenser for utviklingen av estetikken. Arkitekturen står da i fare for å reduseres til overfladiske kulisser uten tektonisk forbindelse til det materielle utgangspunktet (Garmann Johnsen 1995). Økonomiske rammebetingelser legger på ulike måter direkte føringer for arkitektur, og kan pekes ut som en grunn til manglende ressursoptimering så vel som til forflatning av det arkitektoniske uttrykket i dag.

Den markedsliberalistiske økonomien som dominerer produksjon av varer og fysiske omgivelser er basert på kortsiktig profittmaksimering. Til tross for styringssystemer som skatter, avgifter og støtteordninger, underbygger dette rammeverket i utgangspunktet verken arkitektonisk kvalitet eller gjenbrukbarhet for byggematerialer. Det rådende økonomiske systemet er i det hele tatt på mange måter lite egnet til å forvalte materialflyt i et bærekraftig samfunn. Målet om kontinuerlig vekst har åpenbare usunne konsekvenser i utnyttelse av naturressurser, og mange typer råstoff kan umulig lenger regnes som ubegrensede "eksternaliteter" ettersom det viser seg at de faktisk en dag tar slutt. En økonomi for et bærekraftig samfunn bør isteden underbygge miljømessige så vel som etiske målsetninger. Kravet om beregning av livssyklus-kostnader for bygninger kan i denne konteksten være en start for å avdekke manglene ved det eksisterende finansielle rammeverket. I en sunn ressurs-økonomi burde gjenbruk av byggematerialer ha en sjanse til å bli ikke bare miljømessig men også økonomisk lønnsomt. I all vår tro på markedsøkonomi og global handel, er det grunn til å minne om det faktum at lønnsomhet er betinget av det rådende økonomiske rammeverket, og at dette rammeverket faktisk kan endres hvis vi vil.

Konklusjoner

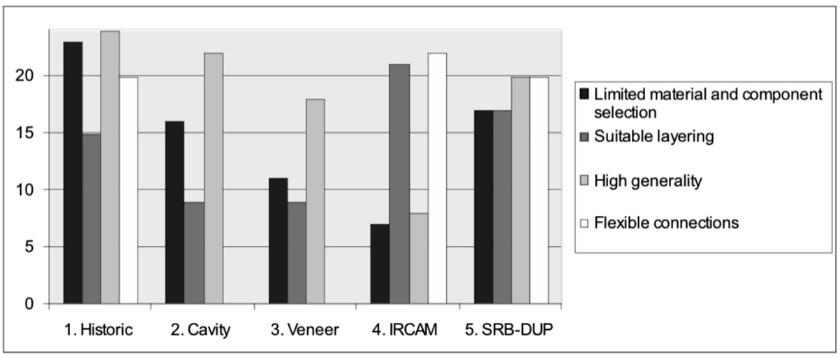
Teglsteinen har mange fortrinn som et miljømessig godt alternativ: Leire er et rikt forekommende materiale og den verdensomspennende produksjonen har lange tradisjoner på en lavteknologisk og regional basis. De ferdig brente steinene inneholder ikke miljøgifter og gir et godt innemiljø, delvis grunnet materialets varme- og fukt-magasinerende egenskaper. I tillegg er teglkonstruksjoner nærmest vedlikeholdsfrie og svært holdbare. Imidlertid er miljøprofilen avhengig av en livssyklus-vurdering slik at den høye energi-belastningene ved fremstilling fordeles gjennom en lang levetid. Derfor bør tenkemåten om en miljømessig forsvarlig levetid legges til grunn, og tilrettelegging for ombruk bør inngå som en del av prosjekteringen. I en fremtidig byggebransje med fokus på bl.a. redusert klimabelastning, vil kanskje ulike former for gjenbruk måtte sannsynliggjøres ved oppføring av nye bygninger. For teglkonstruksjoner er da en overgang til bruk av reversible forbindelser en viktig parameter.

Tegl kan utvikles som miljøvennlig materiale gjennom tilrettelegging for:

- Regionalt distribuerte teglverk, og dermed mindre transport
- Differensiering av kvalitet gjennom ulik brenningsgrad
- Merking av komponentene
- Overgang til muring med kalkrik mørtel eller mekaniske festemetoder

En vurdering av de ulike ytterveggene i oppsettet viser at det ikke er noen opplagte svar på hva som er den optimale teglkonstruksjonen med tanke på ombrukbarhet (Se figur under). Imidlertid kan man peke på noen interessante utviklingstrekk. Den historiske Trondheims-hulmuren fra sluttene av 1800-tallet kommer meget godt ut, definitivt noe urettferdig da de ulike veggene i oppsettet ikke kan sammenlignes når det gjelder U-verdi. Den isolerte hulmuren (case 2) introduseres på 1940-tallet nettopp som et resultat av krav om skjerpet energibruk i driftsfasen. Imidlertid, med flere materialtyper og sementbasert mørtel taper den innenfor alle kriterier for ombrukbarhet. Videre er forblendingsveggen med bakvegg i betong (i bruk fra 1960-tallet) en logisk videreføring av det oppsplittede murverket. Denne løsningen er vurdert til å ha den laveste gjenbrukbarheten av de fem ytterveggene i dette oppsettet. I IRCAM-bygningen fra 1989 introduseres en avansert vegg med demonterbar fasade. Dette konseptet skårer høyt for både fornuftig lagdeling og demonterbarhet. Imidlertid oppstår nye utfordringer i form av mange materialtyper og spesiell detaljering som har lav generalitet. Til slutt viser SRB-DUP veggen fra 2005 relativt gode resultater innefor samtlige kriterier, og kan derfor tilsynelatende virke som den mest lovende ombrukbare teglkonstruksjon for framtiden. Dette resultatet trenger imidlertid et bredere perspektiv.

Vurderingen gjelder ombrukbarhet av teglkonstruksjoner, men ombrukbarhet regnes bare som er ett aspekt under den store paraplyen



Analyseresultater av de fem veggtypene, med poengberegning for hvert kriterium. (For full beskrivelse, se Nordby 2008) som dekker miljøvennlige byggemetoder. Muligheten er - som allltid - til stede for at man i søken etter nye løsninger, utilsiktet skaper nye problemer på veien. Studiet av teglkonstruksjoner kan leses som en historie om sub-optimering; i jakten på bedre varmeisolerende evne mistet man utvilsomt noen grunnleggende kvaliteter ved murverket. En av disse var demonterbarheten, da forblendingsvegger forutsatte sterke mørteltyper. På den andre siden; i jakten på demonterbarhet, ble andre kriterier for gjenbrukbarhet så vel som elementære miljømessige hensyn ikke tatt i betraktning. Hvis vi for å løse ombrukbarhet i en vegg blir avhengig av å anvende store mengder høyt ressursintensive materialer som stål og aluminium slik vi ser i vegg 4 og 5, er det kanskje grunn til å tenke seg om to ganger. Selv om den totale miljøbelastningen for de to alternativene ikke er regnet ut i dette studiet, er det grunn til å tro at den miljømessige investeringen ved å bruke festemidler i stål og/ eller aluminium kanskje ikke oppveier fordelen av enklere rensing av tegl etter demontering. Konklusjonen blir at en videre utvikling av konstruksjoner med kalkbasert mørtel antageligvis er en bedre vei å gå for å oppnå demonterbart murverk.

Som utviklingen av yttervegger i tegl gjennom de siste hundre år viser, er det ikke nødvendigvis noen enkel oppgave å forutse sub-optimering. Idet norske byggeforskrifter rettes mot miljøforbedringer i bransjen, bør man derfor evaluere total bærekraft i et langtidsperspektiv. Helhetlige vurderingsmetoder går lenger enn å beregne energibruk til drift av bygninger, og inkluderer et sett av aspekter angående materialenes livsløp. I et prosjekt i Skottland (Stevenson 2005) er temaer som bygge-effektivitet, avfall, biologisk nedbrytbarhet, energi-innhold, transport og regional kjennskap til materialene vurdert side om side med fysisk ytelse i form av termiske egenskaper, ventilasjon, fukt-balanse, luftkvalitet og akustikk. Demontering, gjenbrukbarhet og avhending kunne videre vært føyd til denne lista over parametre. For å tilfredsstille langsiktige krav til ressurseffektiv materialbruk bør i tillegg det økonomiske rammeverket tilpasses livssyklus-perspektiver framfor kortsiktig profitt. Før norske myndigheter innfører enda strengere forskrifter og anbefalinger angående varmeisolasjon, tetting og mekanisk ventilasjon, trenger vi fler helhetlige studier som kan dokumentere kompleksiteten og de fulle miljømessige effekter av måten vi bygger på.

Avslutningsvis bør det framheves at teglsteinen i seg selv er en utmerket representant for en gjenbrukbar byggekomponent. Den har gode egenskaper i forhold til samtlige kriterier for ombrukbarhet, ikke minst er teglsteinen like enkel som genial for å gi arkitektonisk fleksibilitet. Den representerer et "molekyl"-nivå i byggeriet, et nivå som kanskje på sikt vil tillegges større betydning enn det gjør i dag, både miljømessig og arkitektonisk? En utvikling av kalkbaserte mørteltyper kan være med på å legge grunnlaget for en ny epoke med ombruk av tegl, og kanskje også demonterbar "tørrmur" kan være en løsning i enkelte tilfeller. Spørsmålet er om og i hvilken grad kravene til miljø generelt og til gjenbrukbarhet spesielt vil være med på å forme arkitekturen i framtidens byggeri. Muligvis kan kriteriene for gjenbruk bli en drivkraft for en dypere tektonisk forståelse og et utgangspunkt for å skape god arkitektur. Teglsteinen vil gjennom slike prosesser kanskje forandre seg, differensieres og inngå i nye kontekstuelle sammenhenger, men bør ha gode muligheter til å videreføres som et miljømessig godt byggemateriale.

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