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Edited by Elma Durmisevic

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Preface

University of Twente in Enschede, the Netherlands, hosted the CIB W115 conference on Life Cycle Design of Buildings Systems and Materials from 12-15 June 2009. Unique feature of the conference was its attempt to bridge the gap between the theory and practice in the field of sustainable building construction by involving construction Industry (region of Twente, The Netherlands) into the debate during the conference. Innovation in sustainable construction has been presented through number of case studies by the industry members of the Innovation Platform Twente (working Group IDF). The conference was organized by the University Twente, Innovation Platform Twente (Working group IDF) and CIB.

The emphasis of the conference was on innovative design and construction methods and assessment methods that will incorporate effective use of materials into the whole life cycle of buildings and building materials.

The conventional way of construction has become a burden to the dynamic and changing society of the 21st century. Developers and real estate managers warn that there is a miss-match between the existing building stock and the dynamic and changing demands with respect to the use of buildings and their systems.
A report by the World Resource Institute projects 300% rise in material use as world population and economic activity increases over the next 50 years. Steel price is rising. Raw materials are gradually diminishing and becoming expensive, landfill sites are filling up forcing disposal fees to increase and making the waste management exceptionally expensive.
The physical impact of increasing building mass in industrialised nations and developing world has become undeniable in 21st century. The appetite for raw materials and landfill sites, as well as acceleration of the changing demands by users clearly indicates that a fundamental change in the way buildings are designed and constructed is needed.
During the conference the state of the art papers have been presented with respect to life cycle design of buildings and materials.
This subject integrates issues from spatial adaptability and flexibility of building systems to material efficiency and energy saving (embodied energy).

Development of the research agenda with respect to this topic deal with issues such as, life cycle performance and strategies, design methodology, systems development, reuse, renewable materials, cad manufacturing, and development of performance measurement tools (transformation capacity-measurement tool, life cycle costing, life cycle assessments etc.).

Background on CIB W115

This CIB W115 Commission on Construction Material Stewardship aims to:

- Drastically reduce the deployment and consumption of new non-renewable construction materials, to replace non-renewable materials with renewable ones whenever possible, to achieve equilibrium in the demand and supply of renewable materials and ultimately to restore the renewable resource base
- Carry out these tasks in ways to maximize positive financial, social and environmental and ecological sustainability effects, impacts and outcomes.

Dr. Elma Durmisevic

Sustainable Construction Strategies: A Singapore Perspective

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Abstract
This paper presents an overview of the Sustainable Construction Master Plan envisaged by the Building and Construction Authority (BCA), Singapore. Various initiatives that are currently being pursued to drive sustainable construction are discussed. To highlight strategic Thrust 3, one of the projects funded by the Ministry of Development's Research Fund for the Built Environment is briefly described. The project utilizes microwave heating to increase the yield and quality of recycled concrete aggregates. The preliminary results obtained using the proposed system is briefly reported in this paper.

Keywords:
Sustainable construction, Singapore, Waste to resource, Microwave heating, Recycled concrete aggregates

1 INTRODUCTION

Singapore is a small city state sited on about 700 km^2 of land, supporting a population of 4.6 million people. With one of the highest population densities in the world but practically no natural resources, the development of the city has to be undertaken in a sustainable manner to ensure a first-rate living environment not only for current, but also future generations of Singaporeans.

As most construction materials are imported, concrete has been the construction material of choice due primarily to its lower cost and the availability of low-cost migrant labour employed in the construction industry. Construction materials are generally sourced from regional countries and till recent times, recycled materials were not commonly used in the production of concrete [Annex A].

The global economic crisis notwithstanding, the phenomenon of spiraling construction cost has been attributed to increased global demand and rising costs of construction materials. Coupled with the need to preserve the environment, unlimited supplies of construction materials for urban infrastructure are now no longer viable and sustainable construction is the way forward.

2 SUSTAINABLE CONSTRUCTION MASTER PLAN

Singapore launched the Sustainable Construction Master Plan in 2008 to reduce the use of natural aggregates in building projects through a combination of recycling and more efficient use of materials. To deliver on the twin targets, six strategic thrusts have been identified to drive the industry towards sustainable construction. The six strategic thrusts are:

(1) Public sector taking the lead;

(2) Promoting sustainable construction in the private sector;

(3) Collaborative research & development with industry;

(4) Building industry capabilities;

(5) Strategic profiling and raising awareness to generate sustained demand; and

(6) Setting minimum standards through legislative requirements.

2.1 THRUST 1: Public sector taking the lead

Sustainable development has been and will continue to be a national issue in Singapore and the government will continue to take the lead in efforts to address environmental challenges. An Inter-Ministerial Committee on Sustainable Development comprising government leaders from key sectors, champions the national effort on developing holistic strategies towards sustainable development for Singapore. At the industry level, a Steering Group, comprising representatives from regulatory and government procurement agencies, as well as industry associations, drives policies and other initiatives to encourage the adoption of sustainable construction practices. As the public sector currently accounts for about 30-40% of the total construction demand, it is important for government agencies to take the lead in adopting sustainable construction practices in their projects and showcase these efforts to the industry.

2.2 THRUST 2: Promoting sustainable construction in the private sector

Promotion of sustainable construction in the private sector is mainly being done through BCA's Green Mark Scheme. The Green Mark Scheme is a locally-developed green building rating system to evaluate a building for its environmental impact and performance. Since April 2008, the Green Mark basic standard has been legislated as the minimum mandatory standard for all building works with a gross floor area of 2,000 m^2 or more. Recognition is given in the Green Mark Scheme for the adoption of sustainable construction practices, such as use of construction products made using recycled or environmentally friendly materials.

2.3 THRUST 3: Collaborative R&D with industry

In 2007, Singapore launched a S$50 million Research Fund for the Built Environment, managed by the Ministry of National Development (MND). Research projects that have been approved for funding include the use of recycled concrete aggregates in structural concrete, the conversion of dredged materials and selected industrial waste into synthetic sand and aggregate materials, and the use of microwave technology to improve the quality of recycled concrete aggregates (RCA). To supplement research and development efforts and to test the effectiveness and commercial viability of new recycled products, BCA works with the industry to conduct pilot projects involving the use of recycled products. Examples of pilot projects include the use of recycled materials in an office building project and the extensive use of RCA in a commercial building project for long term monitoring purposes.

2.4 THRUST 4: Building industry capabilities

The success of sustainable construction in Singapore will not be possible without the partnership of the industry in actively adopting best practices. BCA has worked with the Waste Management and Recycling Association of Singapore (WMRAS) to upgrade the standards of RCA-recyclers and accredit them under an industry-led accreditation scheme. The scheme aims to upgrade the capabilities of recyclers, encourage greater self-regulation, and improve the quality and consistency of recycled aggregates. The accreditation scheme was launched in November 2008. BCA is also in the midst of formulating suitable incentive schemes to build up the industry's capability in sustainable construction.

2.5 THRUST 5: Strategic profiling and raising awareness to generate sustained demand

The sustainable construction movement itself will not be sustainable if the demand and awareness within the construction industry cannot be sustained. As part of BCA's efforts to continually educate the industry on the benefits of sustainable construction, conferences and exhibitions have been organized to provide a platform for knowledge-sharing, such as the recent International Solid Waste Association (ISWA)/WMRAS World Congress held in Singapore in November 2008. Singapore will also be holding the International Green Building Conference in October 2009 to showcase and discuss the latest developments.

2.6 THRUST 6: Setting minimum standards through legislative requirements

Although the role of education and promotion is necessary, legislative requirements remain fundamental in determining the advancement of new methods and materials. Previously, the national standard for aggregates was the Singapore Standard (SS) 31: Specification for Aggregates from Natural Sources for Concrete, which covers only the use of natural aggregates in concrete. In March 2008, a move was made to adopt the local equivalent of BS EN 12620: Specification for Aggregates for Concrete, which has provisions for the use of manufactured and recycled concrete aggregates as well. The recognition of the new Standard is crucial for providing guidelines to the industry on the performance of new construction materials from non-natural sources.

In Singapore, older buildings are often demolished to make way for new ones as land use intensifies. As part of BCA's efforts to encourage recovery of higher quality recycled materials, a Demolition Protocol for Resource Recovery, which covers issues such as pre-demolition audits and procedures for sequential demolition and sorting of waste on site, was incorporated into the local code of practice for demolition works. Going forward, BCA will assess the need to implement the submission of a waste management plan for demolition projects, where selected demolition waste materials have to be sorted and sent to accredited recycling firms. This would then ensure a constant stream of recycled materials that can be further channeled for value-added applications.

To highlight the types of projects funded under Strategic Thrust 3 one of the projects funded by the Ministry of Development's Research Fund for the Built Environment is described briefly in the following section.

3 RESEARCH ON MICROWAVE HEATING FOR RCA PRODUCTION

This project is one of a slew of projects funded through Strategic Thrust 3 under the MND's Research Fund for the Built Environment. The main objective of the project is to improve the quality and yield of the recycled concrete production plants in Singapore.

The use of recycled aggregates in structural applications is limited due to the presence of adhering cementitious mortar on the individual recycled aggregate particles. The adhering mortar has been reported to result in higher porosity, higher water absorption, lower modulus of elasticity and weaker interfacial zone (ITZ) between the newly cast cementitious mortar and the recycled aggregates. The method under investigation takes advantage of the differences between the electromagnetic and thermal properties [1 to 8] of the coarse aggregate and adhering cementitious mortar to cause delamination at the ITZ, separating the aggregate from the adhering cementitious mortar. The results of both experimental and analytical studies show that microwave heating is effective in increasing the yield and quality of the recycled concrete aggregates compared to more traditional methods of recycling.

3.1 Analytical results

Analytical modeling was used for the microwave decontamination system shown in Figure 1. The system utilizes three frequencies 2.45, 10.6 and 18 GHz representative of the characteristics of typical low, intermediate and high frequencies together with a constant incident microwave power of 1.1 MW/m^2.

Some of the results obtained are presented in Figures 2 to 4. For clarity Figures 2 to 4 show only the temperature developed within the first 10 cm thick surface layer of the concrete block when subjected to microwave heating.

The amount of energy dissipated in the concrete specimen varies dramatically with its electromagnetic properties. The electromagnetic properties of concrete are a function of factors including concrete ingredients and mix proportions, water content, microwave frequency, temperature, etc. The significant effects of concrete water content (Figure 2 to 4) and microwave frequency on the heating process are confirmed.

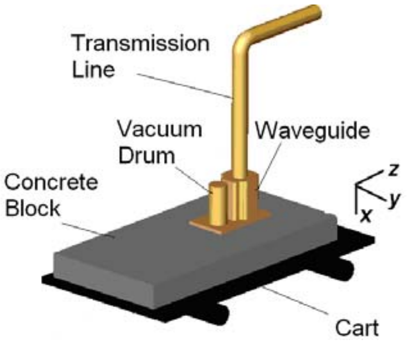

Figure 1: Sketch of the microwave heating system

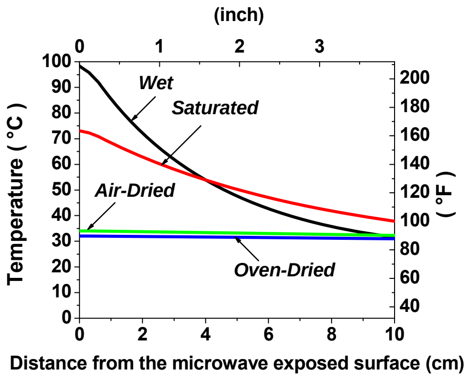

Figure 2: Temperature distribution in concrete after 5 seconds of microwave heating at 2.45 GHz frequency

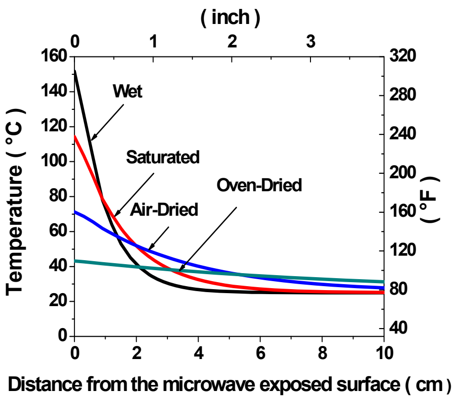

Figure 3: Temperature distribution in concrete after 2 seconds of microwave heating at 10.6 GHz frequency

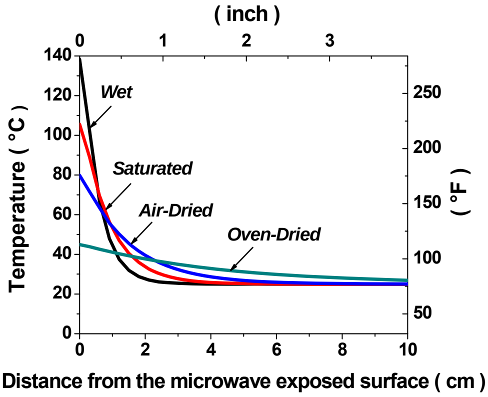

Figure 4: Temperature distribution in concrete after 1 second of microwave heating at 18 GHz frequency

The results indicate that drenching of the concrete surface may be used to increase the efficiency of the microwave decontamination process as considerably higher stresses in a thinner surface layer may be generated in a wet concrete when compared to a dry concrete. However excessive amounts of water may not be desirable as energy would be unnecessarily consumed in generating steam from the surface water present. The temperature reached and the stress generated in the concrete seemed to vary proportionally with the microwave initial power and heating duration.

Typical results plotted in Figure 5 shows the thermal stress development developed within the concrete block. The results confirmed that the stresses developed were significant and sufficient to cause delamination at the concrete surface. The model was expanded to study the concomitant contribution of pore pressure (Figure 6) developed due to microwave heating until concrete surface delamination occurs.

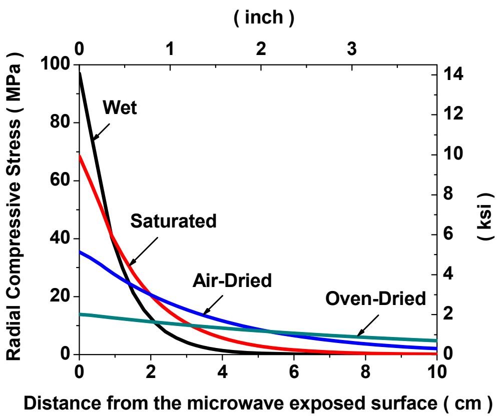

Figure 5: Radial compressive stress in concrete after 2 seconds of microwave heating at 10.6GHz frequency

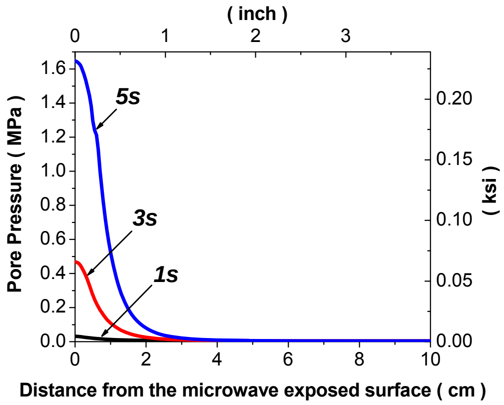

Figure 6: Pore Pressure in saturated concrete after 5 seconds of microwave heating

The feasibility of the new pilot microwave heating system to improve the quality of recycled concrete aggregates (RCA) was investigated by modeling the temperature rise and plotting the temperature distribution in individual RCA particles when subjected to high frequency microwave heating. Typical results (Figure 7) shows that a high temperature differential may be developed in the layer of adhering cementitious mortar, especially at the interface between the natural granite aggregate and the adhering cementitious mortar. These high temperature differentials are expected to result in high thermal stresses at the interfacial zone ITZ and thus are effectively harnessed in detaching the adhering cementitious mortar from the RCA. The spalling depth of the surface layer of the aggregate particle and the microwave exposure time for spalling to take place are inversely proportional to microwave frequency. Once the adhering cementious mortar is delaminated from the surface of RCA, the yield and quality of the resultant aggregates would improve significantly.

Besides numerical modeling, an experimental study is also on-going to verify the numerical results. Preliminary experimental results obtained confirmed the capability of the microwave heating system to remove the adhering mortar within a very short period of exposure. Figure 8 and 9 show samples of aggregate particles after being subjected to microwave heating. The aggregate particles are sieved into various sizes and showed that in most cases the adhering cementitious mortar detached cleanly from the granite aggregates. Light brushing is sufficient to dislodge the loosely attached mortar after microwave heating. The original surface of the granite aggregate was clearly visible under closer examination.

The analytical results obtained yielded results which were of much use as background information for the design of the pilot microwave heating facility to improve the yield and quality of RCA. The processes involved will be further fine tuned to address various decontamination, handling, production, storage and safety issues before a fully functional system may be incorporated for actual production of RCA using microwave heating. This next phase would involve the active participation of an industrial collaborator.

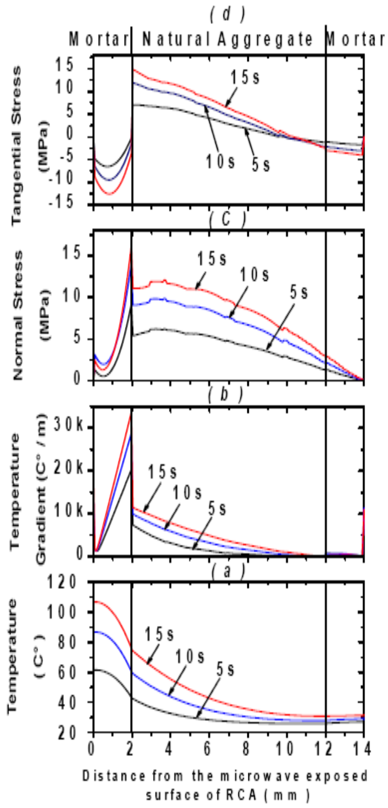

Figure7: Temperature, temperature gradient, normal stresses and tangential stresses developed in a RCA particle subjected to microwave heating at 2.45 GHz frequency and 10 kW power

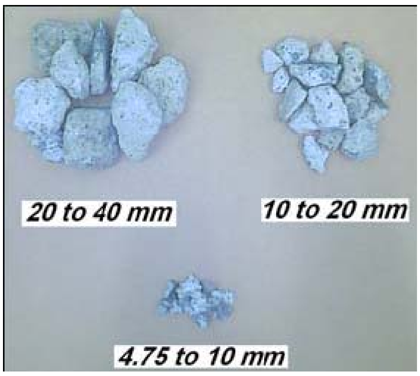

Figure 8 : Granite aggregates obtained after removal of adhering mortar from RCA

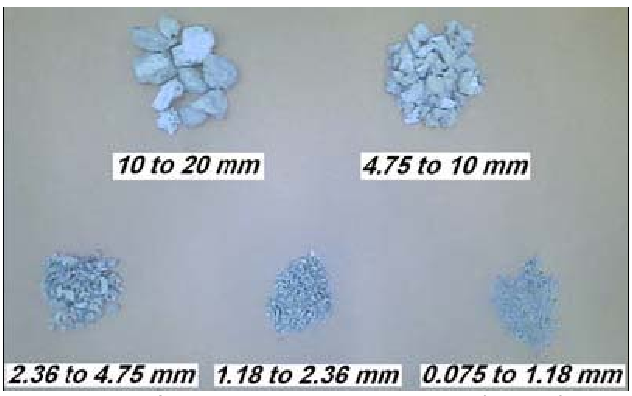

Figure 9: Cementitious mortar detached from RCA

4 SUMMARY

A concerted and holistic approach that covers the whole construction value chain is currently taking shape in Singapore to sustain the supply and demand for recycled materials. BCA has been working closely with the industry to shift from conventional construction methods to sustainable construction. Through tackling design and regulatory issues related to sustainable construction and encouraging the use of recycled materials, the industry has increased its awareness and receptiveness to alternative construction materials and methods. Besides minimizing depletion of natural resources, sustainable construction strategies will also enhance sustainability and preserve natural resources for use by future generations.

5 ACKNOWLEDGMENTS

We extend our sincere thanks to all who contributed to the contents of this paper.

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<u>ANNEX A</u>

CURRENT USAGE OF RECYCLED MATERIALS

The various types of waste materials available for recycling and its current usage in Singpaore's construction industry are briefly discussed below.

A.1 Demolition waste

Demolition waste is the material resulting from the demolition of buildings and other structures. As Singapore's infrastructure ages, demolition waste can be expected to increase. It consists of a mixture of hardcore (concrete, masonry, bricks, tiles), reinforcement bars, gypsum boards, wood, plastic, glass, and other metals etc. The average amount of demolition waste generated is estimated to be 2 million tons per year (based on construction demand of S$17 billion), of which concrete waste makes up about 70% (or 1.4 million tons) of demolition waste. The bulk of concrete waste generated from demolition works is normally used either as hardcore for construction of temporary site access in new construction sites or as materials for road sub-base layer.

Demolition waste in Singapore is relatively uniform based on type of coarse aggregate since granite is the main type of coarse aggregate used for concreting here. Concrete waste, which was manufactured originally with natural aggregates, can be processed into Recycled Concrete Aggregates (RCA) to supplement the use of natural aggregates. However, currently only a small portion of the concrete waste is processed into RCA for use in non-structural precast components such as road kerbs, paving slabs, small drains, etc. Going forward, BCA will introduce various measures and initiatives to promote the up-cycling of RCA obtained from demolition waste for a range of structural and non-structural concrete applications.

A.2 Milled waste

Milled waste is asphalt that has been machine-milled from existing roads. It is bitumen-based and is commonly recycled and reused as a sub-base material for the construction of new roads. The amount of milled waste generated per year is estimated to be 0.5 million tons. Milled waste is currently being explored for recycling under a closed-loop concept where it is processed into Recycled Asphalt Pavement (RAP) to replace part of the aggregates and bitumen used in the manufacturing of asphalt concrete for the wearing and binder courses.

A.3 Spent copper slag

Copper slag is a by-product formed during the copper smelting process. In Singapore, copper slag is imported from various countries by shipyards for grit-blasting to remove rust and marine deposits accumulated on ships. The spent copper slag is then treated and washed to meet criteria imposed by the National Environment Agency (NEA). It can then be explored for further use in other applications or disposed off if no suitable use can be found. NEA requires spent copper slag recycling companies to submit regular Toxicity Characteristic Leaching Procedure (TCLP) test results to ensure that the copper slag has been processed properly. The amount of spent copper slag available for reuse is estimated to be 0.4 million tons per year.

Since 2005, spent copper slag has been used as fine aggregates or sand replacement for concrete production. In using spent copper slag, it is allowed to replace up to 10% by mass of sand (fine aggregates) in the production of structural grade concrete. For non-structural concrete, BCA encourages the use of RCA and spent copper slag to a greater degree, with a replacement rate of 50% by mass of total aggregate content, recognized under the Green Mark Scheme.

A.4 Steel slag

Steel slag is a by-product formed during the steel-making process. It further undergoes a physical process of crushing and separation to produce the required gradation for further use. The amount of steel slag available locally for reuse is estimated to be 0.1 million tons per year. Steel slag can be beneficially used for road surfacing aggregates when it has been properly processed. Since 1994, 100% of steel slag generated in Singapore has been fully recycled into aggregates used in the asphalt mix for the wearing course of roads.

A.5 Incineration ash

In view of the constraints of limited land, Singapore has adopted waste-to-energy incineration as a waste disposal method. Incineration ash, the residual product from the combustion of local municipal solid waste, is currently disposed at Singapore's only offshore landfill at Pulau Semakau. Incineration ash comprises about 15% fly ash and 85% incineration bottom ash (IBA). IBA has to be processed to render it suitable as an aggregate. The amount of incineration ash generated per year is estimated to be 0.5 million tons.

The use of IBA for road construction is currently at the pilot project stage. Successful trials for road usage by the Land Transport Authority (LTA) have been conducted and it was found that treated IBA may be suitable for use as a road base material**.** However, further long-term tests may be needed to monitor the impact of its use on groundwater.

A.6 Excavated & Dredged Materials

Excavated materials are land-based soils generated mainly from construction activities, e.g. earthwork, tunneling. It can be further categorized into 2 groups, namely Good Earth and Soft Clay. Good Earth is used directly as backfill materials or for reclamation purposes while Soft Clay can be mixed with cement to produce a highly flowable grout material (also known as liquid soil) for backfilling and soil stabilization applications. The amount of excavated materials is estimated to be about 3.8 million tons per year. Currently all excavated materials are reused.

Dredged materials are soils excavated under water which consist mostly of marine clay and may contain organic material. The amount of dredged materials ranges from 0.5 to 4 million tons per year, depending on capital and maintenance dredging activities for that particular year. While the non-contaminated dredged materials can be used in land reclamation projects, the contaminated dredged materials are currently disposed at the offshore Semakau Spoil Ground. BCA is currently exploring the use of dredged material for non-structural concrete applications through a R&D project. A new crystallization technology has been developed and patented by a local company to treat and convert dredged marine clay into a ceramic-based product. The newly developed technology is also able to encapsulate contaminants in the materials and covert them into ceramic matrices. On-going research has shown that dredged materials can be manufactured into engineered aggregates with properties similar to lightweight aggregates through a series of physical, chemical and thermal processes. Trial projects will be conducted to determine suitable applications of the material.

From Ugly Duckling to Swan

- Transformation as an Alternative to Demolition

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Abstract
This paper focuses on the transformation of a crude, minimalistic, inefficient 1970s office building into a high quality office tower utilising a fraction of the material resources, and with very significant benefits in both time and cost compared with the construction of a new building. The paper examines the technical processes involved, analyses the triple bottom line sustainability benefits, describes the lessons that have been learnt and explains their application to other buildings of a similar nature both nationally and internationally. It concludes that renovation is not only a sustainable option to the future use of these buildings but that in most cases it is a better option than demolition or even deconstruction.

Keywords
Reuse, renovation, existing buildings, offices, resource stewardship,

INTRODUCTION

Office buildings built in the period 1960 to 1990 were often substandard in terms of their performance materials used and in space. Today, these buildings are quite simply an embarrassment. The general feeling in both the building sector and the community at large is that they should be demolished. Yet they represent a huge investment of resources.

So, is there a resource effective and financially beneficial way of dealing with these buildings? A progressive developer/owner and a skilled design team thought that there was, and transformed a low quality 1970's structure into a 5 star NZ Green Star (New Zealand Excellence) building, which is equivalent to a LEED Gold Standard rated office building. In the process it has been changed from a typical unlovely, unloved and unwanted technically inferior, Brutalist era concrete stub into a crystalline tower that will enhance the urban quality of the area. The scheme will transform the building from an ugly duckling into a swan, in the very best tradition of Hans Christian Anderson.

BACKGROUND

The period 1960 to 1990 saw the creation of generation of cheap and inefficient office buildings. They were commissioned by developer/speculators, who quickly sold them on to building owners. They were built down to the lowest legal construction and space standards at a time of widespread speculative development and space shortages in the office sector. This situation meant that even poor quality office space could find tenants.

While fault is usually assigned to developer/speculators the whole of the building sector must share at least some of the blame for this situation. It could be argued that the organisations that bought and let these low quality buildings and the occupier organisations who rented the space were as much at blame as the speculators. All were interested more in money than quality. All were playing the same game, maximum space for lowest cost; with little consideration being given to the well-being of the end user. Planning controls generally stressed height planes which indirectly encouraged minimal floor to floor heights. The New Zealand Building Code was essentially written around domestic buildings. Builders and designers were required to operate to impossible deadlines and to design or build right down to the cheapest standards included in the Building Code but took the work anyway, were all part of the matrix.

This situation came to an abrupt halt in 1987 when a stockmarket crash was accompanied by a wholesale downsizing of Central Government. Suddenly there was a glut of office space. Many developers went bankrupt and many of those building owners that had invested in low grade office buildings also went bankrupt, because users preferred not to rent these substandard office buildings if other options were available.

Virtually no new office buildings were built in New Zealand in the following 15 years. Instead existing office buildings were upgraded. However, upgrading for the most part was cosmetic in nature with the only energy efficiency improvements in being in the lighting area.

21 QUEEN STREET

Dating from the 1970s, 21 Queen Street is one such marginal value buildings referred to above. Over the years this building and many more like it have become increasingly difficult to tenant. In the case of 21 Queen Street this has led to a prolonged period of decline which has affected not only the building itself but also the area surrounding the building at street level. However it is located in the heart of Auckland's Central Business District and has outstanding views over the harbour from at laest 505 of the office space.

Many developers/owners would have demolished the building and started anew. However the architects ran a series of scenarios and were able to demonstrate to the building owners that a major renovation rather than starting new was the best overall option both in terms of time and cost. In this case, an enlightened client combined with a skilled and imaginative design team found ways to retain the buildings original use and upgrade it to current standards. This has been achieved at a fraction of the cost and time compared with building a new building of equivalent standard.

The design has achieved a NZGBC 5 Green Star 'New Zealand Excellence' design rating (NZGBC 2007), which requires achieving between 60-74 points. In this case the building achieved 65 points. The 5 Green Star NZ rating fulfils the requirements for government office leasing in Central Business Districts and provides the building with a strong marketing cache.

The use of energy efficient lighting, chilled beam space conditioning, water saving technologies, the incorporation of environmentally friendly materials, the building's location adjacent to Auckland's transport hub, harbour and expansive city views and the fulfilment of project management criteria all made strong contributions to the award of Green Star points.

One of the key design decisions was remove the original heavy concrete spandrel panels, as shown in Figure 5, and their replacement with a high performance solar and energy control double glazing façade system that improved energy efficiency, daylighting and glare control and reduced interior traffic noise, as well as presenting a modern image and increasing net lettable area.

The lighter weight of the curtain wall system permitted the addition of 4 extra floors while permitting the retention of the original foundations and structure. These changes allow the addition of an extra 4,500m^2 to the original 14,000m^2 of net lettable space. The existing core is retained and reused and this plus the thinner façade allow a gross to net lettable area ratio 92.5% to be achieved. Together these factors make a major difference to the commercial viability of the renovated building.

The modern, high performance, pressure equalised double glazed curtain wall system (figures 6 and 7) incorporates heat absorbing solar control glass externally and low-E glass on the inner layer This double glazing system permits 51% light transmission and gives a shading index of .29 with a maximum external reflectance of 6% and a maximum interior reflectance of 7%.

Energy efficient, single tube T5 tri phosphor fluorescent lamps are currently specified. These are semi recessed to illuminate and bounce light off the ceiling. The lighting system is designed to allow for the incorporation of LED strip lights as these become available on the NZ market. These will further reduce energy demand. The energy efficient chilled beam air conditioning system uses 100% fresh air and incorporates an energy recovery interface between the exhaust and inlet air intakes which recovers about 68% of the energy and can operate in both cooling and heating mode. The energy recovery system also has a bypass to allow the direct introduction of outside air into the system when this is a more energy optimal mode of operation. This mode can for example be used for night time cool air flushing.

Together these measures have drastically improved the energy efficiency of the building. With buildings of this era base building energy utilisation was around 200kW/m^2/yr Base building energy demand in the renovated building has been calculated at 55.5kWh/m^2/yr, which is roughly 42% of the typical air conditioned base building energy load and well within the NZGBC (PBNZ 2000) target benchmark figure of 120kW/m^2/yr.

Rainwater harvesting and storage is incorporated into the design. A 40,000 litre subsoil tank is installed and will be used for stormwater detention and toilet flushing. Low flow water taps are provided to all bathroom areas.

Figures 1, 2, 3 showing progressive removal of heavy concrete spandrel panels and their replacement with high performance double glazed unitised panels which allowed the addition of 4 new floors of accommodation. Note glazed pedestrian way at ground level that ties scheme into the city.

CRUCIAL DESIGN DECISSIONS

Retained Structure

As noted previously buildings of this era are typical poorly constructed. One major exception to this generalisation is that structural elements always been carefully controlled and built to high and strictly enforced design and constructional criteria in New Zealand. This is necessary because earthquakes and high winds can be both frequent and severe. Due to this condition the whole structure was able to be reused. This in itself saved months of construction time and a very significant quantity of material resources. In this type of building the massive, reinforced concrete structure, floor slabs and foundations conventionally contribute 75% or more to the building's total embodied energy content (Storey 1995).

Replacement of concrete spandrel panels

A key element in the economic refurbishment of the building was that it was originally constructed with very heavy precast non-loadbearing concrete spandrel panels and obviously the structure was designed to take the loadings imposed. Therefore the removal of these panels and their replacement with much lighter full height high performance glazing allowed four floors of extra lettable space to be added to the height of the building without changing the structure. This combined with the extra space due to the use of thin rather than a thick wall resulted in an extra 4500m² of net lettable space being generated in the building which made the whole scheme economically viable despite the resulting building being some 40 metres less in height than was allowed with current height regulations.

Retained Structural Core

Core size is another crucial factor. In buildings of this era the core provides most of the sheer strength of the structure. In many buildings the core is as dimensionally mean an as all other parts of the construction. If it had been necessary to beach the structural core, to meet user demands for vertical services and lifts/escape stairs the scheme would have been rendered financially unfeasible. Fortunately, in this case the structural core was just large enough to take all the extra servicing requirements and the modified lifts able to meet the reduced lift waiting times demanded by today's tenants.

Improved Floor to Ceiling Height

The original building had a floor to ceiling height of 2400mm which is now deemed unacceptable by users. In the original design scheme the underside of the slab and the services were exposed which allowed a floor to ceiling height of 3000mm. However the client considered that it was commercially unacceptable to dispense with a ceiling. The design team managed in the end to incorporate a ceiling and increase the floor to ceiling height in the existing building to 2650mm.

Air Conditioning and Ventilation

A chilled beam heating/cooling water system with a separate ventilation system was selected for the building. The ventilation system uses 100% outside air but incorporates a energy recovery interface. This interface recovers about 67% of the energy which is used to precondition the incoming air. A bypass system This provides

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Transforming Cities: Introducing Adaptability in Existing Residential Buildings through Reuse and Disassembly Strategies for Retrofitting

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Abstract
Since the existing building stock will remain with us for decades, their importance as economic, social and cultural capital should not be wasted. In the framework of the current ecological and social issues, residential buildings need to be re-designed and adapted according to their environmental impacts. However, the lack of flexibility in the conventional building design does not enable these crucial transformations, often causing demolition of building parts or entire building structures.
The aim of this paper is to specify a systemic design approach to update residential buildings, extending their initial material and energy consumption while integrating future adaptability. Reuse and potential reconfiguration of building products provide answers to the increasing construction and demolition waste issues. Through a case study of retrofitting of a semi-high-rise residential building, the opportunities using disassembly and reuse strategies are being explored, by stripping the building to its bearing structure and adding a new adaptable infill, composed of reconfigurable and reusable building components.

Keywords:
4 Dimensional Design, design for disassembly, material and component recovery, reuse of existing buildings, transformation

1 INTRODUCTION

To produce our buildings, finite resources such as petroleum products, minerals and water are being consumed in high rates. As the world's population is continuing to grow, the depletion of the earth's material and energy resources will continue to increase, leading to degradation of our natural environmental and human health. The built construction world is a sector that is responsible for a high contribution to the consumption of these natural resources. New construction, maintenance and renovation of buildings, including the production of building materials, generate 45% of the European waste [1] [2].

In addition, traditional buildings are unable to answer the variable factors of everyday life, the changing social needs and evolving functional requirements of the building, due to the current static building design. Lack of integrated flexibility and adaptability often causes demolition of major building parts or even demolition of entire buildings. As a result, the conventional building design is responsible for a vast amount of redundant construction and demolition waste - an amount that is still increasing, as the number of building activities increase yearly.

Consequently, the construction and demolition waste represents, for example in Flanders (Belgium), the largest fraction of the total waste disposal composition [2]. This growing tendency has been observed in several European countries.

Regarding demolition of buildings, it is identified that buildings, no longer satisfactory in terms of spatial, functional or formal requirements, may still incorporate numerous materials containing various lifecycle benefits [3]. To bypass the wasteful processes of demolition and reconstruction, reuse of entire buildings must therefore set as a priority, and subsequently, reuse of the building's components and materials must be maximised.

The process of adapting old structures for alternative uses, thereby extending the useful life of the existing building stock and their components, supports key concepts of sustainability by lowering material, transport and energy consumption and pollution. Indeed, since buildings usually last for decades, the importance of the existing building stock as an economic, social and cultural capital should not be wasted. Although their environmental impact has been estimated significantly higher than new buildings [4], the number of new buildings constructed annually in developed countries barely corresponds to 1,5 - 2 % of the existing building stock. This means that even with strategies that replace all existing buildings with more energy and material efficient new buildings, at the current construction rate it would take from 50 to 100 years to replace the entire current building stock [5].

It is therefore important to introduce new strategies that minimise the impact of the existing buildings, integrating a long term vision and creating new opportunities.

This paper discusses a general approach for reuse of existing buildings, integrating adaptability and reuse of building components, with the focus on (social) high-rise housing.

2 4 DIMENSIONAL DESIGN

2.1 From fixed to demountable structures

Due to the conventional building design, the world of today is facing the environmental impacts of our short term building design vision and excessive consuming construction environment. Alternative building design strategies are needed that take a total life cycle of buildings into account. The reuse of building components in adaptable constructions clearly presents environmental, social and economic benefits, compared to the demolition of traditional buildings.

The main problem regarding adaptability, disassembly and reuse is the fact that over the past decades designers conceived buildings as being fixed and permanent. They did not make any provisions for their future adaptation or disposal. The lack of **design for adaptability** and **disassembly** in current buildings is therefore a major barrier to effective transformation and deconstruction for reuse. To increase the building's transformation capacity and allow reuse of building components, building design will be primarily different from traditional design methods.

4Dimensional design (4D) refers to a design attitude to conceive 'objects' from a long term vision, therefore integrating the fourth dimension, i.e. *time*, in the initial design phase [6]. As a result of evolving circumstances, there is a growing need for buildings to adapt themselves in spatial as well as in structural terms. 4D strategies conceive building artefacts that support evolving processes in life and society instead of predetermined designing for a specific situation. Possible change over time is therefore being incorporated from the first stages of conception of a building and its components. These design strategies take into account buildings' life cycles on three different levels - material, component and artefact and introducing adaptability, reuse and recycling [6].

This design vision enables different possibilities for reuse of materials and components on different levels of the built environment (Figure 1): [7]:

- relocation and/or reuse of an entire building;
- reuse of major parts of a building - renovation of a building;
- reuse of components in a new building or elsewhere in the same building ;
- reprocessing of components and materials into new components - recycling of materials into new materials.

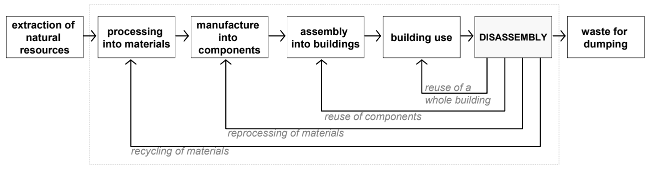


Figure 1: Different possible reincarnation scenarios in the built environment [7].

Figure 1 shows that on the highest level or reuse, the primary step to achieve a sustainable built environment is to consider 4D approaches for the **reuse of the existing buildings** (reuse of entire building).

3 A 4 DIMENSIONAL DESIGN FOR ADAPTIVE REUSE OF EXISTING BUILDINGS

3.1 An alternative approach to reuse of existing buildings

Approaches to reuse the existing buildings, need to intervene in the existing building stock in a way that these buildings can again participate in a positive environmental development.

Research has shown that the existing building stock has the greatest potential to lower the environmental load of the built environment over the next 20 to 30 years, particularly as a result of performance upgrading of the existing buildings [4]. The vast majority of social high- rise buildings erected in the 1970's in Flanders are in an urgent need for renovation. The small-format interior layouts and the inflexible (outdated) typologies with fixed technical facilities suitable in those days are no longer accepted by the current users and buyers. As infill development increases, more individuality and freedom of expression in housing is being claimed. However, changing spatial configurations in the current structural conception of buildings currently still means a material consuming and expensive intervention [8].

Therefore a 4Dimensional Design approach is proposed for the renovation process of high-rise housing supporting the natural evolution of the resident's needs while minimising its environmental impacts. The proposal makes use of the existing bearing structure of the building as a *support* with empty plots for a new adaptable *infill*, independent of the old structure. The infill can exist of different typologies of dwellings, designed according to the individual needs of the inhabitants. These dwellings are set up using a construction kit based on the HENDRICKX and VANWALLEGHEM approach (further discussed in 3.2), allowing each dwelling to interact with the individual (changing) needs of the inhabitants.

The 4D designed renovation kit supports the different present functional layers in constructions. It is fundamental to introduce a physical separation between the existing bearing structure and the new infill, its technical facilities, etcetera, since the different building parts carry out different functions and have characteristic life spans. In present buildings, fast-cycling components, such as for instance, dividing walls, can experience conflicts with slow-cycling building parts, for example, the structure of the building, when they need to be adapted. In that case, not only the affected components will need to be repaired or replaced, but several adjacent and connecting elements will have to be removed as well [9]. Brand [10] therefore introduces a conceptual framework to divide a building into different lifespan layers (Figure 2), with different functions, characterised by their anticipated need for modification. The separation of constructions in six shearing functional layers, namely *Site, Structure, Skin, Services, Space plan* and *Stuff*, allows layers to be changed over time without affecting the other layers [9][10]:

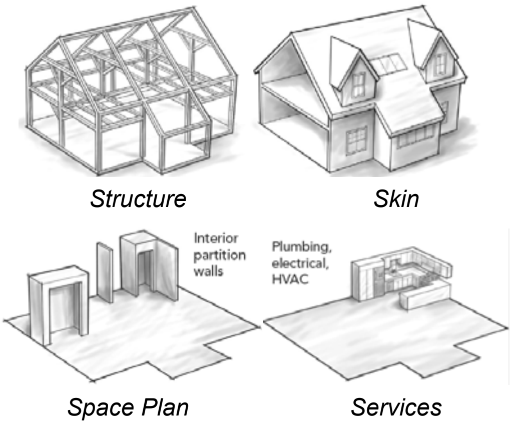


Figure 2: Shearing layers of change in buildings [11].

For the approach of the case of existing high-rise housing buildings, a specific interpretation is given to the formulated functional layers of Brand:

- Considering the global construction, SITE$_1$ and the (bearing) STRUCTURE$_1$ are predefined in existing structures and are consequently unchanging layers for this case.
- A primary global SKIN$_1$ definition indicates the decision-making on the level of the global new infill of the structure through variable typologies of housing.
- The primary SERVICES$_1$ and SPACE PLAN$_1$ layers indicate the interventions for the global circulation organisation and the technical distribution organisation of the entire building structure.
- Thereafter, on a secondary scale regarding the *individual* dwellings, a further layering can be made into (secondary) STRUCTURE$_2$, SKIN$_2$, etc.

Different guidelines for Design for Adaptive Reuse will be further discussed on the primary and secondary level of the 4 global functional layers for this case: STRUCTURE$_1$, SERVICES$_1$, SPACE PLAN$_1$ and SKIN$_1$.

It is put forward that in this paper only a selection is presented of the most critical measures to be taken for adaptive reuse.

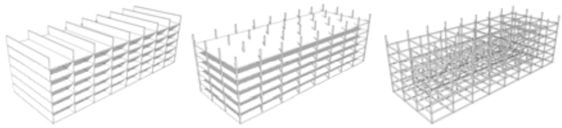
3.2 Guidelines for a 4D approach of existing high-rise housing buildings

Reuse of a Building (STRUCTURE$_1$)

High-rise buildings are favoured with a logical ordered bearing construction in good structural condition. The extent of work required to revive a problematic building (such as moisture problems in the structure) would cause it to not be cost-effective.

In a first step, the original building is stripped down to the bearing structure, creating empty plots, as a support for the new infill of various housing typologies. Direct reuse of the removed elements should be maximised, and subsequently, recycling of the materials of damaged components into new ones.

A structural analysis has to be made of the stripped bearing structure to remove all non-structural walls, columns, beams, etc., respecting the stability and the stiffness of the building. This will allow minimising the existing structure's impact on the new independent infill. Different types of bearing structures will have characteristic implications on the possibilities of a new spatial organisation of the building. For instance, a skeleton structure (Figure 3(c)) allows more vertical flexibility than a structure characterised by bearing walls and floors (Figure 3(a)).



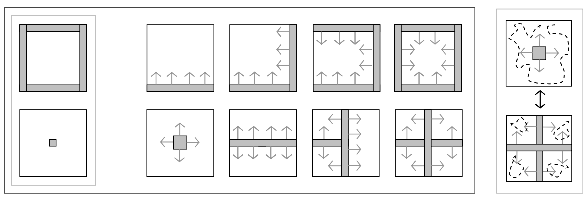
(a) (b) (c)

Figure 3: Types of bearing structures in semi-high-rise buildings: (a) bearing walls and floors structure; (b) bearing columns structure; (c) skeleton structure.

Adaptive Reorganisation of a Building (SERVICES$_1$, SPACE PLAN$_1$)

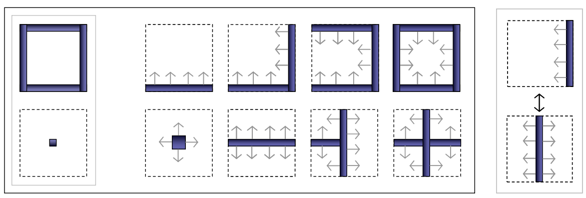
The existing bearing structure needs to support a large variety of infill configurations. Therefore, the (re)organisation of the building needs to be given additional attention. Regarding the access per storey to the dwellings, different variations can be considered between extremities; Figure 4(a) shows variants between a minimal centralised access and a maximised circulation through the perimeter of the floor-plan. As a result of the space positioning, some variations offer a higher rate of flexible partitioning. Figure 4(b) depicts a centralised access to the surrounding zones, offering a greater organisation freedom for the configuration of apartments, than for instance a double linear circulation organised in the centre of the building floor plan. To create a flexible support, the designer therefore has to make a legitimate choice between different possible variations, according to the opportunities in the considered bearing structure.

Regarding the distribution of technical services (water, electricity, etc.), analogue organisation schemes variable in flexibility can be formulated (Figure 5(a)-(b)).



(a) (b)

Figure 4: (a) Horizontal circulation organisation illustrated by an example (b) of a flexible centralised organisation versus a fixed double linear organisation.



(a) (b)

Figure 5: (a) Organisation of the distribution of technical services illustrated by (b) a flexible centralised linear

distribution organisation versus a linear lateral distribution.

Multi-use construction kit for adaptable infill of existing buildings (SKIN$_1$)

The new adaptable infill of the bearing structure (support) is built up using a construction kit designed applying the Hendrickx and Vanwalleghem approach [12]. According to this approach, to enlarge the possibilities of reuse of these components it is of major importance to design these components from a non-specific and non-contextual approach, and to focus on systematisation and standardisation of form and dimension. Therefore, two useful design tools are being considered: a *generating form and dimensioning system* and *theoretical design catalogues*.

First, every building component has to be considered as an assembly of functional basic elements with multiple life spans, designed using a set of standardisation rules. The *generating form and dimensioning system* ensures full compatibility of form and dimensions between all basic elements. Hendrickx and Vanwalleghem presume that any basic element, in any construction phase, can be approximated with a minimal diversity of basic forms: the *square*, its *diagonals* and the *inscribed circle* (Figure 6). In order to achieve optimal flexibility and combination, this set of basic forms is provided with basic dimensions obtained using the rules of either halving or doubling, creating geometrical series [12].

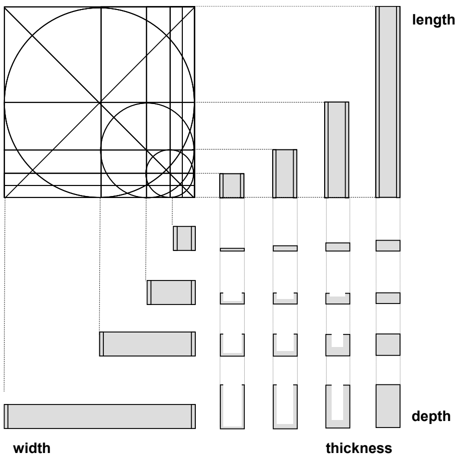


Figure 6: Designing basic elements such as a structural beam through a fractal model of the generating system.

Applying this standardisation model on all material solutions increases the opportunities of reuse of buildings and their components after deconstruction significantly, because of the higher potential of exchangeability.

To simplify and rationalise the reuse of basic elements, it is advantageous to make use of systemised catalogues of constructions systems (i.e. a grouping of all possible variations within a chosen set of basic elements). Therefore the construction elements of each material solution are objectively and verbally described, based on characteristics, strengths and weaknesses [12]. Each characteristic has one or more parameters as a counterpart, all ranged between predefined limits. This can be illustrated with the example of the bearing capacity of a steel corrugated plate, subject to transverse loads. This can be described with three parameters: *its thickness, the number of waves per unit length and the height of the waves*. These parameters can be entered into series by defining the extreme values.

This approach can be applied to an entire construction. The concluding result is a set of design catalogues, each one based on combinations of selected parametric rules. They allow choosing basic elements based on their formal and functional characteristics.

3.3 Case Study: Building n° 9 of Cité Modèle, Brussels (Belgium)

SPACE PLAN$_1$, SERVICES$_1$ and SKIN$_1$

A feasibility study of the described design approach for existing buildings is done through a virtual renovation project for (semi-) high-rise buildings.

Building n° 9, situated at “Cité Modèle” in Brussels (Belgium) is representative for many semi-high-rise housing buildings in Flanders. As a result of the static design of these types of buildings, adequate living conditions have been obstructed after several years of use. The small-format interior layouts do not longer answer the current surface regulations for social housing, and offer few typology variations for different family compositions.

Since the analysis of Building n° 9 has revealed that the thermal and acoustic performances of the building are minimal, it is preferable to entirely replace the existing building envelope and infill. The proposition consists of stripping the building to the bearing skeleton, removing all non-bearing structural elements and preserving the staircases and the elevators for the global stiffness of the building. This provides spatial freedom for the new infill of individual housing. The individual dwellings that will be reinserted independently of this structure, can thus reconfigure, expand or contract inside the open plan structure, when fundamental changes would occur in the socio-economical situation of the inhabitants. The open plan also enables the introduction of various dwelling typologies for different family compositions.

The existing circulation zone to the different dwellings is organised through two centralised zones for each storey, accessible through the staircases and the elevator. This initial circulation organisation is preserved, because it minimises the space loss due to circulation zone, offers sufficient access to all dwellings and gives a high spatial flexibility of different housing typologies around this access zone.

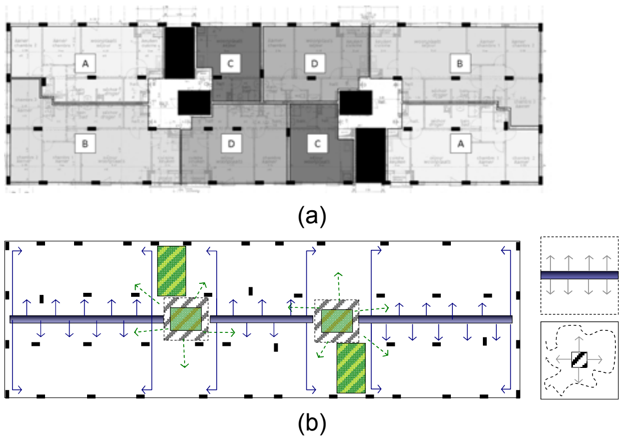
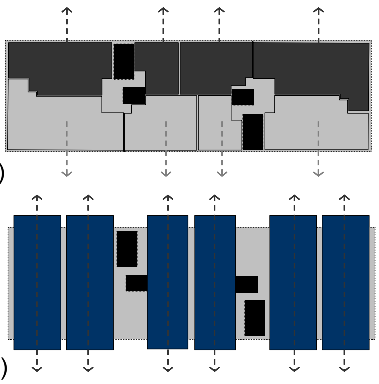


Figure 7: (a) Typical floor plan of building n° 9 at “Cité Modèle” (Brussels) with current plan with 4 fixed dwelling typologies; (b) Reorganisation of the circulation and the distribution of services of building n° 9, providing a flexible basic plan.

The distribution of services (water, electricity, etc.) is organised linear through the longitudinal axis of the building (Figure 7(b)). Consequently, it is possible to provide technical services in diverse spatial configurations of the dwellings, using a minimal distribution length for cables, plumbing, etc. An efficient and flexible distribution of technical services becomes possible to the surrounding rooms, perpendicular on the longitudinal axis.

The connections for the sanitary facilities are provided along this central longitudinal axis, in order to group the facilities where natural daylight is not required, allowing the remaining living spaces to be organised along the façade. Secondary sanitary connection points are provided along the existing internal bearing walls, given the permanent character of these walls.

The general organisation enables the realisation of transverse apartments in the 4D renovation proposal. Transverse apartments posses various advantages compared with the existing unidirectional typologies: the comfort for the users is increased since natural ventilation can be achieved and a diversified interaction between the use of the rooms and the orientation of the building is possible [13].



(a)

(b)

Figure 8 (a) Unidirectional apartment configuration in current Building n° 9; (b) Transverse apartment in the renovation proposal for Building n° 9.

SPACE PLAN$_2$, SKIN$_2$ AND SERVICES$_2$

The global flexible organisation of each building level allows the implementation of a variety of housing scenarios and enables individual dwellings to function independently of the structure, so that they can reconfigure, expand or contract inside the open plan structure, when in time important changes occur in the socio-economical situation of the inhabitants.

Figure 9 shows a range of possible scenarios providing different dwelling configurations to the users of the building.

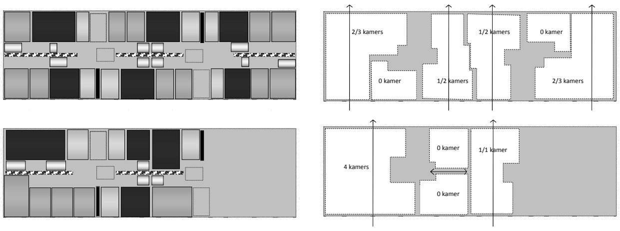
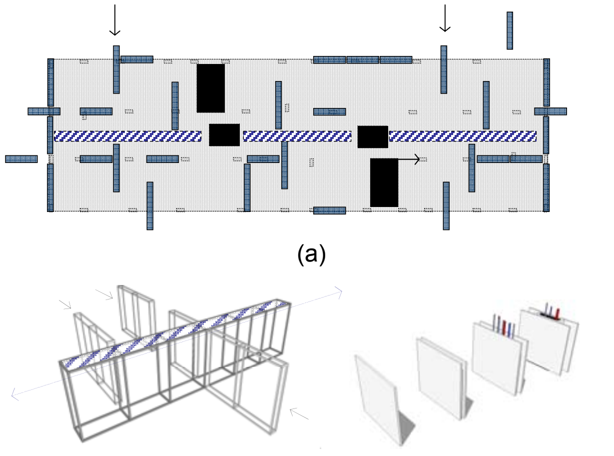


Figure 9: Different scenarios for the infill of a floor level of Building n° 9.

The stripped bearing structure of Building n° 9 is characterised by a confined storey height of 2,49m. This means that it is not possible to insert flexible technical solutions in the floors/ ceilings, without reinforcing the initial lack of useful storey height. Flexible technical facilities are therefore integrated in the further discussed wall system.

The global concept for the infill of the main building structure consists of inserting a primary longitudinal functional axis, providing all supply and transport facilities, and providing plug-in appliances for the insertion of the secondary walls and the sanitary facilities (Figure 10 (a)). Both primary and secondary wall configurations have the potential to integrate technical services and are therefore conceived as a multi-layered wall element, built up with the same basic elements and configured according to the applied scenario (Figure 10 (b),(c)).



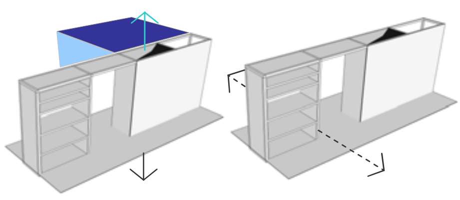
(a)

(b) (c)

Figure 10: (a) Conceptual introduction of functional walls plugging-in on the primary longitudinal distribution axis; (b) Materialisation of primary and secondary functional walls; (c) Multi-layering of walls.

The primary longitudinal axis consists of a three dimensional frame, filled in with different functional layers, depending on the scenario of the surrounding rooms. Regarding the relations between the adjoining spaces and this primary frame, four main situations can be distinguished:

1. enclosed infill; to define a separation between two different spaces
2. open frame; where a passage between spaces is needed
3. technical infill; to provide technical shafts over the different floor levels
4. functional infill; to provide built-in items such as closets and storage space



(a) (b)

Figure 11: Examples of functional infill of the primary longitudinal functional frame.

The secondary walls that plug-in perpendicular on the main axis are variants on the primary frame. They can be configured as internal dividing walls, common walls between apartments or external walls, using the same basic elements. To insert the internal walls, an independent layer of modular floor and ceiling panels is foreseen in the bearing structure, respecting the existing grid of the building (module 1,04 x 1,04 cm). Upon this first layer, a secondary structural frame can be placed (dry connected) and filled-in with prefabricated demountable panels (Figure 12).

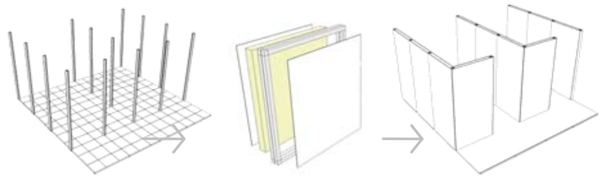


Figure 12: Assembling the internal walls with dry-connected prefabricated wall panels.

The design of this structural frame enables typical connections in buildings (Figure 13). Depending on the required thermal, acoustic, and technical performances, the configuration and materialisation of the secondary structural frame and of the panels can be chosen from a set of design catalogues based on the HHV strategy, each one based on combinations of selected parametric rules. The detailing of the secondary structure allows the use of alternative panels, of altered materials (wood, steel, plastic), each with particular thermal and acoustic behaviour and specific environmental impacts.

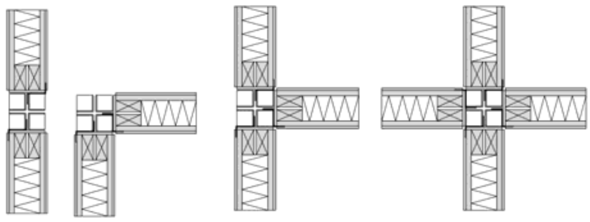


Figure 13: Example of (a) a catalogue of a wooden wall configuration panel of 16cm thickness.

The overall new infill, consisting of the primary axial framework, the secondary wall structure and the wall panels, is built up using dry connections to combine the basic elements to building components. This enables adaptation, reconfiguration and finally, reuse of these building components. For instance, the electrical cabling is provided in a narrow void behind the finishing layer of the wall and the prefabricated wall panel, which enables adaptation of this fast-cycling technical layer without demolishing the entire walls. As a result of the dismountable character of the finishing layer, the technical layer can be easily adapted and reconfigured.

This high rate of wall flexibility will also enables further performance upgrading when building legislation changes occur in the future; by altering or adding elements, different building physics, improved acoustics, fire resistance, etc. can be achieved without significant demolition processes.

4 SUMMARY

Currently, the implementation of an alternative 4Dimensional approach into the design of buildings is of major importance since the building sector of today is dealing with serious environmental issues. Strategies that consider changing preconditions in a building's service life need to be integrated in the new built constructions of today, but maybe even more in the existing building stock since it will remain with us for several decades.

To make exchangeability and (multiple) reuse of building components achievable in practice and to allow adaptability of constructions through reconfiguration, design should focus on standardisation of form and dimension of the basic elements of construction systems on one hand, and on the use of building components composed by dry assembled compatible basic elements on the other hand.

Although this case study focuses on the particular problem of semi-high-rise housing buildings, this design methodology can be transferred to the framework of other types of existing buildings. Construction kits developed for existing buildings can be expanded to the field of new construction, when additional characteristic building components are being designed.

However, for an adequate evaluation of the results of this conceptual 4D design approach, it is crucial to put these design guidelines in practice in a further stage.

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Requirements for Sustainable Construction Materials and Components

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Abstract
Under the focus of construction material stewardship, negative environmental impacts in construction arise, among others, due to various construction waste streams. With this respect, efforts in practice as well as in science are undertaken to foster the development of new construction materials, paying respect to the requirements set by the need for a sustainable development. In the paper, outcomes of a Delphi study among experts with experience in the field of architecture supported by a literature study are presented. In particular, requirements for construction materials will be elaborated. Thereby, the focus is drawn to the ecological as well as economic dimension of sustainability. Ecological aspects attached to construction materials stewardship comprise required characteristics of construction materials with respect to environmentally friendly behavior during and after use. In contrast, economic factors focus on, among others, cost and flexibility. A third category was raised by the target group: “architectural and engineering requirements” which are however only briefly addressed and the paper.

Keywords:
Construction materials, life-cycle, sustainability, requirements

1 INTRODUCTION

Under the focus of construction material stewardship, the construction industry is characterized by a high material intensity due to the heterogeneous mix of construction materials and components inherent in buildings and the related construction and demolition waste streams.

The tremendous impact of the construction industry becomes obvious considering aspects like resource deterioration as well as congestion of landfills. Additionally, negative environmental impacts arise due to various construction waste streams. With this respect, efforts in practice as well as in science are undertaken to analyze current construction materials and to foster the development of new construction materials, paying respect to the requirements set by the need for a sustainable development.

In the paper, the focus is drawn to the ecological as well as the economic dimension of sustainability. Thereby, ecologic aspects attached to construction materials stewardship comprise required characteristics of materials in order to avoid negative ecological impact. In contrast, economic factors focus on cost but also quality factors and associated terms like eco balancing and life cycle costing. Therefore, the whole life cycle of a construction material has to be taken into consideration.

Furthermore the paper will elaborate on the outcome of a Delphi study on sustainable construction materials among experts with experience in the field of architecture.

2 IMPACT OF THE CONSTRUCTION INDUSTRY

The negative effects of construction activities can be categorized as follows [1]:

- Resource deterioration: depletion of forest resources by the use of timber; dereliction of land caused by quarrying; extraction of sand, clay and other deposits such as limestone; use of energy in the production and transportation of materials and in site construction activity;
- Physical disruption of ecosystems and long-term climatic changes: diversion of natural waterways caused by dams, loss of flora and fauna, and upsetting of the ecological balance with possible

health hazards; noise pollution caused by buildings in urban areas; affection of stability of fragile hillsides by highway construction;

- Chemical pollution: particles released in the production and transportation of materials such as cement and quarry products; pollutants produced in the production of building materials; fibers released during working with asbestos products; accidental spillage of chemicals on site and careless disposal of waste.

It becomes obvious that the construction industry must actively react in a positive manner to environmental issues. Actions to be undertaken include [2,3]:

- Arresting the depletion of resources, e. g. timber and clay, through economic use of resources as well as recovery of materials and the use of renewable varieties;
- preventing and arresting pollution by a proper waste management, the development and use of non-polluting materials, as well as by applying suitable techniques for construction, maintenance and demolition; low pollution or no-waste technologies;
- exploring energy sources for the extraction of raw materials and the production of materials, the construction activity as well as for the use, maintenance and deconstruction of buildings.

In addition the environmental factors, the economic component of construction materials has to be taken into consideration as well; i.e. environmentally sound construction materials will only find widespread use if its economically reasonable to use these materials for the construction contractors (apart from laws and regulations in force).

3 RELATED WORK

Intensive research has already been undertaken with respect to the sustainability of buildings, its components and materials. Thereby, the focus of research mainly addressed the sustainability of buildings or its components in terms of ecological impact throughout the whole life cycle. The most common measures used were energy use and embodied energy.

3.1 Sustainability of buildings

Analysis and research on life-cycle energy and embodied energy use or the related energy efficiency of buildings were undertaken, for instance, by Chen et al. [4] for a residential building in Hong Kong, by Yohanis and Norton [5] for a single-storey office building in the UK, by Sartori and Hestnes [6] as a review for conventional and low-energy buildings, by Thormark [7] as life-cycle analysis of a building including recycling potentials, by Scheuer et al. [8] undertaking a life-cycle energy and environmental performance analysis of a new university building, as well as by Meillaud et al. [9] who evaluate a building using the emergy method.

3.2 Sustainability of building components

Components were addressed by Weir and Muneer [10] with an energy and environmental impact analysis of double-glazed windows, by Wilson and Young [11] on the embodied energy payback period of photovoltaic installations in the U.K., and by Crawford et al. [12] as life-cycle energy analysis of building integrated photovoltaic systems.

3.3 Sustainability of building materials

Furthermore, building materials were addressed by, e.g., Harris [13] introducing a quantitative approach to the assessment of the environmental impact of building materials, by Huberman and Pearlmutter [14] as life-cycle energy analysis of building materials in the Negev desert, by Venkatarama Reddy and Jagadish [15] for the embodied energy of common and alternative building materials, by Morel et al. [16] who address the use of local materials and its impact on the environmental impact of construction, by Cole and Rousseau [17] using indices for building materials referring to energy and air pollution, as well as by Abeysundara et al. [18] who present a matrix for selecting sustainable materials for buildings in Sri Lanka on a life-cycle perspective.

4 DIMENSIONS OF SUSTAINABILITY OF MATERIALS

As can be seen, research most commonly focused on the analysis of the environmental performance of buildings, its components and materials using energy measures. However, looking at the three columns of sustainability materials – ecological, economic, and social dimension – a much wider scope which should be considered within the context of sustainability of building materials occurs. Thereby, requirements for building materials with respect to sustainability have not only to be considered but also need to be classified according to these dimensions. However, due to the interdependencies of some requirements (e.g. well-being as social mean also includes the use of non-hazardous-materials which is most often referred to as ecologic aspects) overlapping of the dimensions occurs.

Hence, the criteria named in the following can by no means classified exclusively as ecologic, economic or social. However, the illustrations given put special emphasize on the most suitable dimension with respect to the highest correlation of impact on the sustainability of building materials and components. Thereby, it is not note, that in addition to the requirements mentioned, sustainable materials and components still have to comply to requirements regarding safety (such as health protection), quality (e.g. durability, resistance), and DIN norms.

4.1 Ecological Requirements

Ecological requirements raised by the experts interviewed were:

- Recyclability
- Contamination

- Insulation and thermal conductivity
- Deconstructability

Recyclability

The construction industry is the second largest consumer of raw materials after the food processing industry [19]. Construction materials are highly diversified and accumulate in huge amounts at the end of the life cycle either of the material or of the building or its components. In Germany, the Waste Management and Recycling Act (KrW-/AbfG) [20] defines a hierarchy for waste treatment. The highest priority is assigned to the avoidance of waste. Second ranked is recovery or recycling of materials (§4). However, construction materials can still not lead back into the material cycle without any processing, or even have to be disposed off. Hence, the ability of recycling of a construction material is a prerequisite for the establishment of closed-loop material flows.

However, a prerequisite for the recycling of the construction materials is the existence of incentives for the disposal at recovery facility. Hence, the user has to be provided with a functioning and affordable, or even beneficial in terms of refund, take back system. Unfortunately, due to the high costs associated with such a take back system for C&D waste leads to a draw back in the establishment of these systems in the construction industry, which, naturally would have to pay for it [21].

Contamination

The aspect of contamination refers to the environmental burden caused by construction materials but also to its impact on the well being and health of the living environment. In the past, construction materials were used for interiors without giving cause to possible negative effects. However, nowadays, several of the construction materials used in the past are now known to be hazardous to health and environment. Among these substances are asbestos, polychlorinated biphenyls (PCB), polychlorinated terphenyl (PCT), polynuclear aromatic hydrocarbons (PAH), as well as wood preservatives like lindan and pentachlorophenol (PCP). The use of numerous substances is already interdicted, however, the number of negative symptoms caused by indoor algerns and toxins in the interior of buildings has risen significantly [22].

Thereby, to avoid energy loss in buildings, building envelops, doors and windows are tried to be sealed as good as possible. If these buildings do not have appropriate ventilation, the concentration of indoor pollution increases.

With this respect, the Construction Products Directive contains regulations not only about building materials. testing and approval but also contains requirements regarding hygiene, health and environmental protection on a European basis, which are, however not yet being implemented into guidelines and norms. Hence, the implementation of health and environmental protection is only at its beginning [22]. Standardized methods for the assessment and approval of contaminant content of construction materials are still missing. Particularly in Germany, steps are taken by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety who fund projects undertaken by the German « Öko-Insitut » as well as by the « Deutsches Institut für Bautechnik (DIBt) » which is a member of the EOTA (European Organisation for Technical Approvals) and of UEAtc (The European Union of Agrément).

Insulation and thermal conductivity

The requirements for construction materials with respect to insulation and thermal conductivity are permanently increasing. Especially in the field of retrofitting, a high potential exists with respect to high insulation with at the same time low material thickness. Not only indoor emissions can be decreased with improved insulation and thermal conductivity, but also costs for heating might be decreased which strongly interrelates with economic requirements [22].

Not only with respect to heat but also with respect to noise, insulation is considered to be an important criterion for sustainable construction materials and components. However, it is claimed that although efforts to protect people from noise have been undertaken, the situation has not significantly improved during the last years [22]. Here as well, overlapping of the ecological as well as social dimension of sustainability occur, as increased exposure to noise might lead to health damages. Noise decreasing actions might include the use of sound absorbing walls, doors, windows and roofs.

Deconstructability

Already in the ancient world, buildings had been deconstructed and construction materials had been recovered and reused. For example, one can find columns from every epoch of the Greek architecture in the cistern of Istanbul [23]. For the easy deconstruction, however, single components are not only needed to be designed for deconstruction, but also compound materials have to be easy resolvable and enable a non-destructive deconstruction.

Compound materials as used in practice are not always sustainability in terms of resolvability and non-destructibility. A proposed solution is to foster prefabricated building and modular housing.

4.2 Economic Requirements

Economic requirements as perceived to be important for the experts interviewed comprise:

- Availability
- Manufacturing and price
- Flexibility
- Life time expectancy

Thereby, these requirements are not only achievable in terms of cost savings but also with respect to time savings during construction projects.

Availability

The availability of construction materials has a strong impact on costs as well as on the construction time of a building. Thereby, on the one hand, a high availability reduces purchasing effort and on the other hand leads to quick lead times, even if orders are made on short notice. Low availability would present an obstacle for construction contractors to use these materials. Furthermore, the availability refers to local aspects. It might be beneficial to use local materials rather than materials which have to be delivered from far distances, with respect to transportation effort and costs (which in turn is beneficial for the environment due to reduced emissions during transport) [19].

Manufacturing and price

In addition to a high availability, construction materials and components ought to be cheap in production, hence, should not be significantly or even cheaper than its less sustainable substitutes. Keeping the idea of closed-loop material cycles in mind, subsidies for the use of recycled or renewable raw materials should be encouraged, whereas the price for primary resources should be increased, which however, has a positive impact on the environment.

Flexibility and multiple purposes

The flexibility of construction materials addressed the opportunity to be able to use the materials for different purposes. The high flexibility could lead to an increase in the demand for a particular construction material, hence, to a larger production, and, hence, the realization of cost reductions due to economies of scale. Prices could decrease and the demand for these sustainable materials would increase as result of market mechanisms.

Life time expectancy

Although high life time expectancy might as well be an ecological requirement in terms of reduced material use due to longer replacement intervals, construction materials and components with a long life cycle and low maintenance effort reduce investments for maintenance, replacement and renovation.

4.3 Further Requirements

Based on the practical experiences of the experts participating in the Delphi study, a third category was raised: “architectural and engineering requirements”. These aspects consider characteristics which are related to the use of construction materials for particular design and engineering purposes. These aspects, besides the ecological and economic requirements, where mentioned to be significantly important for future efforts to develop sustainable construction materials and components. Thereby, it is to note that these requirements are also related to economical as well as ecological requirements.

Especially for façades, a high durability with low maintenance was required. In practice, developments for self cleaning coatings exist [23].

Also the bearing capacity plays a role by the development of sustainable construction materials in the future. Despite materials already existing, a high bearing capacity with smaller cross-sections for easy handling and more innovative design of buildings were mentioned to be important too.

5 SUMMARY

In the paper, results of a Delphi study among experts with practical background in architecture were presented. With this respect, the requirements for sustainable construction materials and components could not be classified as solely ecological or economic. However, the most appropriate dimension was chosen. A high emphasis was put on the economic requirements by the experts, though ecological requirements are usually put in the foreground in research about the sustainability of construction materials and components.

Nevertheless, the existence of these requirements does not ensure sustainability of construction materials and components itself. Approaches and methods have to be applied to examine and proof whether and to what extend the requirements are fulfilled. Different methods existing are, for instance, quality management, eco balancing, labeling and life cycle analysis. These would have to be further analysed regarding their scope and suitability for the different criteria.

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Building green via design for deconstruction and adaptive reuse

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Abstract
This paper discusses the imperative need in today's construction industry to create a design for deconstruction and design for adaptive reuse credits in United States Green Building Council (USGBC) Leadership in Environmental and Energy Design – New Construction (LEED-NC) point system that allows projects that are designed for adaptability and deconstruction to earn points towards the green building certification. Earning LEED points can be a substantial incentive for owners and architects to think about designing new buildings for adaptation and deconstruction.

Keywords:
Sustainability, LEED, Deconstruction, Adaptive Reuse, Green Construction

1 INTRODUCTION

Deconstructing a building aims at recovering the building materials while maintaining their quality at the end of the building's useful life; therefore reusing different salvaged building materials and recycling of the waste. Reusing a building targets its reconfiguration to accommodate a different use thus considerably reducing the consumption of resources and waste generation. Not only that deconstruction and adaptability ultimately lessen the world's depleting energy and natural material resources, they also contribute to preserving the cultural and historical values inherent in different materials and buildings**.**

Today, projects can only earn points in LEED-NC for deconstruction or adaptive reuse through the Innovation and Design category. However, the environmental, economic, and even social outcomes of designing for adaptive reuse or deconstruction deserve a better recognition. The United States Green Building Council (USGBC) should recognize the magnitude of these outcomes and capitalize on them by offering credits for designing for adaptive reuse and deconstruction in the Material and Resources category in its LEED-NC assessment system.

As a result, the objective of this study is to propose two separate credits, for a total of six points, for designing for adaptive reuse and deconstruction in the Material and Resources category in the LEED-NC assessment system. By doing so, owners, investors, and stakeholders will be more willing to invest in pursuing these points and in return expanding their environmental gains and benefiting from the long-term return on their investment.

2 BACKGROUND

2.1 Environmental Concerns

In order to promote sustainability and reduce the environmental impacts by reducing the consumption of finite resources, experts in sustainable construction agree that the most efficient way to reach that goal in the construction industry is to close the materials loop. The closed-loop is a recycling concept that should be the ultimate goal of the recycling industry in order to maximize the usefulness of the existing used materials and reduce the need to extract and produce raw and virgin materials.

According to Kibert, there are distinct construction materials that are explicitly used only in the construction industry, such as aggregates and gypsum drywall, and thus their reuse and recycling are limited only to construction [1]. As a result, closing the material loop in the construction industry tends to be a bit more challenging than the case in other industries due to the cycle uniqueness of some construction materials

2.2 Embodied Energy and CO2 Emissions

Embodied energy, measured in KJ/Kg, is the energy required to extract, process, manufacture, and even to transport a product. It is considered over the material's life cycle from extraction all the way to installation. In addition to all the raw materials that need to be extracted, the extraction process itself, moving this much earth and refining it, and transporting thousands of tons of construction material from their source to the construction site requires significant energy inputs.

CO_2 emissions are generated during energy consumption, and embodied CO_2 is based on specific energy sources of a process. CO_2 emissions leading to green house gases that cause climate change typically occur with embodied energy.

What the industry needs is a new mental model that weighs the used construction materials as valuable resources worth harvesting in a manner that preserves there embodied energy and the CO_2 already invested in those materials [2]. Nevertheless, the subsequent process of harvesting used construction materials itself should not cause inordinate amounts of CO_2 and embodied energy otherwise the very purpose of salvaging construction materials will be defeated.

2.3 Green End-Of-Use Options

The end of the building's useful life generates a stream of used materials that can be reprocessed for new construction. The selection of materials for reuse or recycling should not start at the end of the building's life cycle. It should start at the design stage. Architects and engineers should keep the whole life cycle of the building in mind and select construction materials based on their capacity to be reused or recycled after the building has served its purpose [3].

Building Reuse

It revolves around repairing a building to accommodate a new use rather than tearing it down.

Component Reuse

It requires maintaining the majority of the interior nonstructural
elements such as interior walls, doors, floor coverings, ceiling systems and so on to be used in a similar or different application at the end of the building's useful life.

Material Reuse

A direct reuse of the materials after the deconstruction of the structure in new or existing structures allows them to retain their current economic values, reduces the embodied energy required to recycle, and minimizes the need to extract new mold raw and virgin materials by reducing carbon footprint and cutting into resource use

Material Recycling

The degree of which increasing the recycled content actually has an environmental advantage is subject to the specific type and source of each material. Recycling consists of three different routes: down-cycling, recycling, and up-cycling. Each one of these routes requires energy inputs and result in waste and emissions depending on the material itself.

3 LEED-NC

The official definition of LEED according to the USGBC is," The LEED® (Leadership in Energy and Environmental Design) green building certification system is a featureoriented
certification program that awards buildings points for satisfying specified green building criteria" [4]. Currently LEED is the primary point-system building assessment method that rates the building's performance based on its environmental impacts, resource consumption, and building health in the United States. Currently, green projects pursuing a LEED-NC certification are rated based on LEED-NC version 2.2. LEED-NC 2.2 consists of six major categories and seven pre-requisites, and a total of 69 points. The points reflect the weight experts place on the different major issues that each category entails. The weight of each LEED-NC credit is established, through the existing consensus process, as part of a systematic, continuous improvement cycle for LEED-NC based on advances in green building science and technology and an expanding base of experience and evidence.

In regards for deconstruction and adaptability, currently LEED-NC does not directly address those two concepts in as a stand-alone credit or as a multi-part credit. As mentioned previously, points for deconstruction and adaptability can potentially be earned in the Innovation and Design credit in LEED-NC.

4 DESIGN FOR ADAPTIVE REUSE

4.1 What is Design for Adaptive Reuse

There are a number of reasons that cause building modifications, renovations, and even a complete destruction via classical demolition methods such as explosives or demolition ball. Reasons range from the change in ownership, alternate demography and residential units, to future growth and expansion. Therefore, the building no longer serves the purpose it was constructed for and thus its demolition or at least modifying its layout becomes inevitable.

The adaptability of any building depends on its design, form, materials, and the extent to which a building is appropriate for its purpose. The building's capacity for adaptability is usually affected by its structural design, the different services within, its finishes, the internal layout, and its external appearance.

Designing for adaptive reuse requires designing for the recovery of the majority of the building's components i.e. exterior walls, roofs, foundations, decking, exterior skin and frames and so on. It also requires designing for recovery of the majority of the interior non-structural elements i.e. interior walls, doors, floor coverings, ceiling systems and so on. In short, designing for building adaptive reuse should ideally expose the building's structure to minor changes while undergoing major renovations and modifications.

4.2 Why Design for Adaptive Reuse

The more flexible and adaptable the building is to different uses and occupiers, the longer its useful life will be and that has economic and environmental investments over time. In the past decade, the concept of buildings' adaptive reuse gained importance due to the rapid change in both private and public organizations types of work that demands more inventive and flexible work place designs. It was also due to the increase in rebuilding costs, the focus on the environmental drawback of new buildings, and the effects of obsolescence. Therefore, designing for adaptive reuse permits renovations based on parameters that preserve the structures' material values with more or less success in order to host a new function.

Building Performance

Buildings that are not capable of adapting, with minor changes in their structures, to different circumstances from technological, demographic, or even environmental, are at risk of becoming obsolete and poorly utilized thus unable to serve a purpose at their current phase.

This may require major renovations and in some cases complete demolition and new construction thus increasing the use of resources within the building sector by 20 to 30% [5].

Nevertheless, there are multiple ways that a building's performance can be enhanced via designing for adaptive reuse. Buildings designed for adaptability ideally have a much better use of space and materials during their life cycle. Designing for adaptability increases the flexibility of spaces allowing the occupants to use the floor areas more effectively. Also, studies have shown that most buildings get demolished for their inability to adapt to new technologies not for structural deterioration [5]. Designing for adaptability elongates the lifetime of a building without having to go through renovations that significantly affect the integrity of the structure and infrastructure thus minimizing the environmental impacts. Also, Designing for adaptive reuse allows the building to adjust, at lower costs, to new technologies that become available.

Environmental Benefits

The traditional demolition methods of buildings that can no longer serve their original purpose create large volumes of building material debris that usually end up in landfills. In addition to that, the demolition process itself is harmful to the environment because it can release contaminants or particulate matter that can potentially affect air and water quality. Also, the process of extracting new construction materials, manufacturing, and transporting them to the site increase the overall energy consumption and release green house gases that ultimately contribute to global warming.

One of the main advantages of reusing a building is the retention of the original buildings embodied energy [6]. Existing buildings have certain levels of embodied energy in the construction materials used. When reusing a building, the embodied energy of the building materials is retained, thus making the project much more sustainable than an entirely new construction. Therefore, new construction has significantly higher embodied energy costs compared to buildings that have been adaptively reused.

Economic Benefits

Wilkinson and Reed ask the following, “How do you determine whether a building is going to be more expensive or less expensive to carry out adaptive reuse?” [7]. Many researchers argue in favor of the adaptive reuse of buildings and consider its economic benefits as equally appealing as its environmental ones. Studies have shown that adapting a building for a different use significantly lowers the initial costs for the purchase and transportation of new materials for a new build [8]. The cost of labor is reduced depending on the complexity of the building and therefore reducing the amount of structural modifications required to accommodate a new function. Also, significant savings in time can be noticed in excavating and rebuilding major elements when reusing a building.

Gary Pokrant states that adaptive reuse is not only good for the communities involved, it is also a smart economic choice [9]. He argues that when a building is adaptable, renovations take place quicker and are significantly less expensive than demolition and new construction since the building’s utilities, infrastructure, and major structural components are still in place.

All of the above, according to Pokrant, yields a more marketable project that gets a faster return on the money invested in building it

4.3 Design Strategies for Adaptive Reuse

The American Society of testing and Materials (ASTM) provided guidelines that architects and engineers are recommended to follow in order to design for adaptive reuse of a modern building [10] [11] [12]:

- Design spaces such that minimum disruption will be caused to occupants due to physical change;
- Design luminaries to facilitate of relocating within ceiling grid or when up-lighting is used;
- Design air diffusers on flexible ducts for easy relocating at minimum cost with minimum disruption to occupants;
- Design exhaust air ducts for special exhausts for easy reinstalling - space and capacity should be available in ceiling and duct shafts;
- Design sprinkler heads to facilitate easy relocating within ceiling grid;
- Design pre-wired horizontal distribution systems in ceilings or floors, with spare capacity and easy access to accommodate change of workplace layouts;
- Design for easy relocation of partition walls that causes minimum damage to flooring or ceiling systems; and
- Design partition walls to be easily removed and fully salvageable.

This paper sheds light on promoting designing for adaptive reuse among the different construction sectors by suggesting an incentive that might be environmentally and more importantly economicly appealing. This research suggests incorporating designing for adaptive reuse as a multi-credit category in LEED-NC. The economic, environmental, and social benefits of a building’s adaptive reuse are substantial and therefore need to be addressed directly in LEED-NC assessment system.

5 DESIGN FOR DECONSTRUCTION

5.1 What is Design for Deconstruction

The overall objective of designing for deconstruction is to reduce the environmental impacts such as pollution from the demolition of buildings, and to increase the stream of used and recycled building materials through designing for the recovery and the eventual reprocessing of building materials. The idea is to employ design practices that facilitate the recovery of materials with high capacity for recycling and reuse in order to selectively and systematically deconstruct buildings that would otherwise be completely or partially demolished at the end of their useful lives.

5.2 Why Design for Deconstruction

Designing for deconstruction requires architects and engineers to select materials that have a high capacity for reuse in subsequent projects and materials that are recyclable and reprocessed into new products whether or not in the construction industry thus ultimately closing the materials loop. The selection of materials by building designers should take into account the results from different environmental assessments such as embodied energy, closing the materials loop, and so on in order to identify the most environmentally friendly stream of construction materials.

Environmental Advantages

Designing for deconstruction is a tool for reducing the environmental burden by designing for the recovery of materials that have the capacity to be reused or recycled. As a result, designing for deconstruction facilitates the achievement of different environmentally cautious results such as closing the materials loop, reducing the embodied energy and emissions of CO_2 and finally minimizing the ecological footprint required for the lifecycle of the different building materials. According to a study done by BioRegional Development Group in the United Kingdom, the potential for salvaging and recycling building materials thus eliminating the need for new materials is enormous. The study suggests that reclaiming, reusing, or recycling materials can save up to 95% of their embodied energy [13].

Economic Advantages

The labor and equipment costs for deconstructing a building can get expensive depending on the complexity and location on the project. However, since designing for deconstruction aims at maximizing the diversion of materials from landfills, this helps the owner or developer minimize the tipping fees which in return offsets to a great degree the labor and equipment costs associated with deconstructing the building. Another appealing economic incentive for designing for deconstruction is the return on the value of salvaged building materials. This requires establishing a market for salvaged materials with values that are competitive with other alternatives.

Needless to say that the resale value of materials designed for recovery at the end of the building's life cycle is crucial. Therefore, designers can promote designing for deconstruction by choosing materials that have high quality and will have a high dollar amount return when recovered in the future. The value of many recovered resources depends on the robustness of the local recovered materials markets, which varies a great deal historically.

5.3 Design Strategies for Deconstruction

Guy and Shell provide architects and engineers with some design strategies for facilitating deconstruction of buildings [14].

- Nails and bolts have appropriate uses as per the type of connection and size of the members. Fewer connectors and consolidation of the types and sizes of connectors will reduce the need for multiple tools and constant change from one tool to the next.
- Long spans and post and beam construction reduce interior structural elements and allow for structural stability when removing partitions and envelope elements.
- Doubling and tripling the functions that a component provides will help "dematerialize" the building in general and reduce the problem of layering of materials.
- Separating long-lived components from short-lived components will facilitate adaptation and reduce the complexity of deconstruction, whereby types of materials can be removed one at a time, facilitating the collection process for recycling.
- Elimination of caulking and sealants and hightolerances in the connections can be offset by the ease of removing components for repair and replacement, and designing in durability, using mechanical instead of chemical-based water protection.

The goal is to make designing for deconstruction mainstream and a trend in building design practices. One day, building owners who designed their buildings for deconstruction might look back with great appreciation towards architects and engineers who took the extra step beyond the conventional designs that usually end building lives as expensive liabilities, but instead employed design practices and building resources that facilitated the recovery of materials for profitable future reuse.

6 RECOMMENDATIONS

Building elements are defined as major building parts e.g. roofs, vertical structures, walls, floors, or foundations. Building components are defined as the next level of nonstructural
building parts such as interior walls, doors, floor coverings and ceiling systems. Sub-components are a breakdown of components into their smaller pieces such as the duct systems of heating and cooling systems, the hardware for a door unit, or the sash of a window unit. Finally, materials are defined as the constituent materials from which all other elements, components, and subcomponents
are made, such as plastics, metals, wood,
and masonry.

This study proposes two additional credits in the Material and Resources category that exclusively address design for adaptive reuse and design for deconstruction in LEED-NC, awarding a maximum of six points distributed equally among both categories towards a LEED-NC certification. The Materials and Resources category has seven existing LEED credits thus the proposed credits will be MR Credit 8 – Design for Deconstruction and MR Credit 9 – Design for Adaptive Reuse.

The proposed credits require designers, architects, and engineers to establish a plan that capitalizes on construction design practices that facilitate the deconstruction or the adaptability of a building and utilize the use of the hierarchy of the end-of-use options for buildings, elements, components, subcomponents, and materials respectively. Ideally, the design process should act as an independent level of information that specifies exactly what the types of materials and components are used in the construction process and adopt construction strategies that architects and engineers believe best facilitate the deconstruction and adaptability processes.

6.1 LEED-NC and Design for Deconstruction

This paper recommends that the proposed deconstruction credit contains of a weight factor (W.F.) for each end-of use option, an achieved product (A.P.), the percentages of materials with the capacity for reuse, up-cycle, recycle, and down-cycle, and finally, the points associated with the total sum of the achieved products. The percentages of materials are based on the materials weight (in tons) in relation to the weight of the entire building. The achieved product is a result of multiplying the weight factor of each end-of-use option by the weight percentage of materials associated with that option.

The five end-of-use options for building materials and the weight factor associated with each option are illustrated in Table 1 below:

End-of-Use Options	Weight Factor
Reuse	8
Upcycle	6
Recycle	4
Downcycle	2
Landfill	0

Table 1. End-of-Use Options and Their Weight Factors

Table 2 below illustrates the amounts of LEED-NC obtainable points associated with the achieved product.

Achieved Product (A.P.)	LEED Points
A.P. < 1.5	0 points
1.5 ≤ A.P. < 2	1 points
2 ≤ A.P. < 2.5	2 points
2.5 ≤ A.P.	3 points

Table 2. Achieved Product and LEED-NC Points

MR Credit 8: Design for Deconstruction

The following is a detailed description of what MR Credit 8 entails.

MR Credit 8: Design for Deconstruction

1 – 3 Points

Intent

Establish a sustainable deconstruction plan by employing design strategies that facilitate the ease of disassembly of buildings with the capacity for material reuse or recycling thus reducing the demand for raw materials, minimizing waste, and reducing environmental impacts resulting from the extraction and processing of new materials

Requirements

Maximize the achieved product (A.P.) via the ease of disassembly of different building systems, modular construction, minimizing materials use and selecting building materials with the capacity for subsequent reuse or the potential for recycling and reprocessing at the end of the building's useful life

Potential Technologies and Strategies

Include components that are field connected using easily removable mechanical fasteners. Avoid using materials that are connected using field-installed adhesives or welds unless they may be easily removable to permit material reuse. Avoid nails by using screws and bolts especially in wood frame connections. Minimize the use of cast-in-place concrete and grouted, reinforced masonry and masonry laid in portland cement mortars.

SUBMITTALS

- Deconstruction Strategy Statements – details the anticipated disassembly process and includes a thorough description of the different strategies that architects and engineers devised to ease the disassembly of the material and the end of the building's life cycle.
- A list of Building's Elements, Components, and Materials – includes the specifications of the elements, components, and materials used in constructing the building in addition to their expected service life, weight, end of life options e.g. reuse, recycle, or landfill, and a recommended handling strategy when salvaged during the deconstruction process.
- A Set of the Deconstruction Blueprints and Drawings – for facilitating the deconstruction process by including all the design and specification information necessary. Information may include key structural properties, locations of wiring systems, and photographs of connections use in construction of the building and so on. Ideally the blueprints should be digital, made readily available, and kept up to date.

Calculations

% of materials reused (1)

$$= \frac{\text{Materials designed for reuse (tons)}}{\text{Total weight of the project (tons)}} \times 100\%$$

% of materials up-cycled (2)

$$= \frac{\text{Materials designed for up-cycling (tons)}}{\text{Total weight of the project (tons)}} \times 100\%$$

% of materials re-cycled (3)

$$= \frac{\text{Materials designed for re-cycling (tons)}}{\text{Total weight of the project (tons)}} \times 100\%$$

% of materials down-cycled (4)

$$= \frac{\text{Materials designed for down-cycling (tons)}}{\text{Total weight of the project (tons)}} \times 100\%$$

% of wasted materials (5)

$$= \frac{\text{Materials ending up in a landfill (tons)}}{\text{Total weight of the project (tons)}} \times 100$$

6.2 LEED-NC and Design for Adaptive Reuse

In order for the project to earn the point associated with this credit, the recovery of a minimum of 75% to 95% of building elements and 50% of the interior non-structural components are recommended by this study. The preceding percentages are determined by the architects and engineers at the design stage based on the square footage of the components designed for retaining and the total square footage of the area containing those components. For instance, interior non-structural components reuse is determined by dividing the total proposed area (sq. ft.) of retained interior non-structural components by the total area (sq. ft.) of the entire interior, nonstructural components included in the completed design.

The same formula applies towards determining the percentages of the retained building elements. In short, architects and engineers should design a flexible building that has the ability to adapt more than 75% of its exterior shell and a minimum of 50% of its interior non-structural components during its life cycle to major renovations leading to a new building use with minor changes to the structural integrity of the building.

Also, the different adaptability design strategies that architects and engineers implement should be consistent with the American Society of Testing and Materials' guidelines provided in their E1692-95a, E1679-95, and E1334-95 international designation standard practice.

MR Credit 9: Design for Adaptive Reuse

The following is a detailed description of what MR Credit 9 entails.

MR Credit 9: Design for Adaptive Reuse

1 - 3 points

Intent

Coordinate designs for building interior modules and building structural system that permit reconfigurations of space layout increasing the longevity of buildings, improving its operating performance, and allowing for spatial flexibility for future reuse.

Requirements

MR Credit 9.1 – ADAPTIVE REUSE: Maintain 75% of Building elements

1 point

Design for maintaining 75% of building elements based on surface area such as existing walls, floors, and roofs in the structure and envelope

MR Credit 9.2 – ADAPTIVE REUSE: Maintain 95% of Building elements

1point

Design for maintaining an additional 20% (95% total based on surface area) of building elements such as existing walls, floors, and roofs in the structure and envelope.

MR Credit 9.3 – ADAPTIVE REUSE: Maintain 50% of Building's Interior

1 point

Design for reusing 50% based on surface area of the interior non-structural components of the building.

Potential Technologies and Strategies

Design the building for flexibility by choosing a structural system that allows spaces to be reconfigured such as simple consolidation of MEP service points within the building reducing the length of lines and the points of entanglement and conflict with other elements. Consider also designing access pathways for changes to building utilities and infrastructure. Adopt the "open-space" concept when designing offices with modular wall panel systems.

Submittals

At the design stage, submit:

- Reconfiguration strategy statements - Architects and engineers shall provide statements presenting detailed strategies as to how and to what extend the building's structural and spatial adaptability is provided.
- A list of building's elements, components, and materials - includes the specifications of the elements, components, and materials used in constructing the building in addition to their expected service life and a proposed handling strategy during the building's rehabilitation process.

- A set of the reconfiguration blueprints and drawings – Architects and engineers shall include building plans and detailed specifications. The blueprints and drawings shall elaborate specific design strategies justifying the intended outcome. Ideally the blueprints should be digital, made readily available, and kept up to date.

Calculations

% of interior components (6)

$$= \frac{\text{Components designed for adaptive reuse (sf)}}{\text{Total area of interior components (sf)}} \times 100\%$$

% of structural envelope (7)

$$= \frac{\text{envelope designed for adaptive reuse (sf)}}{\text{Total area of structural envelope (sf)}} \times 100\%$$

Reference Standard

- ASTM International Designation E1692-95a Stand ard Classification for Serviceability of an Office for Change and Churn by Occupants
- ASTM International Designation E1679-95 Standard Practice for Setting the Requirements for the Serviceability of a Building or Building-Related Facility
- ASTM International Designation E1334-95 Standard Practice for Setting the Requirements for the Serviceability of a Building or Building-Related Facility

7 SUMMARY

Aside from their environmental advantages, designing for adaptive reuse and deconstruction add short term economic and possibly environmental costs to the project, but on a bigger scale of the lifecycle of the project, the long term benefits of utilizing those two concepts outweigh any initial costs.

The USGBC should recognize the magnitude of these outcomes and capitalize on them by offering two separate credits, for a total of six points, for designing for adaptive reuse and deconstruction in the Material and Resources category in its LEED-NC assessment system.

8 ACKNOWLEDGMENTS

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Developing the Stavne Timber Block;

Life cycle design in practice

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Abstract

This paper reports on a development project where a prototype building component in massive wood [1] is being redesigned for full scale production. By utilizing reclaimed wood, the environmental efficiency of local material loops is improved. The component facilitates flexibility in construction and user phase, and also future reuse. Furthermore, the block intervenes with work adaptation in the production line as well as with life style and identity for the users. Through simplicity of construction, the block supports self-building and thus economic feasible dwellings. The paper describes the criteria for the development process, and discusses their influence on construction method.

Keywords:
Massive wood components, Carbon-neutral, Closing the loop, Work training, Self-building

1 INTRODUCTION

1.1 The Concept of the Timber Block

A building block based on stubs and reclaimed wood is introduced and described by architect Bjørn Berge as „Klimablokka" (The Climate Block") [1]. The building system aims at carbon mitigation by addressing life cycle design, low-impact material use and production as well as carbon storage. The prototype Timber Block is made up by cross-laid boards, fastened by wooden dowels. The construction method is described as a stacked system, where the components are joined by plugs.

In contrast to contemporary massive wood components that are usually provided in large-scale and often custom-made for each project, the Timber Block system aims at suitability for self-building. Also, future flexibility and reuse is facilitated. In the end, as wood-burning stoves are installed in as much as 80% of Norwegian dwellings, heat recovery is an obvious option.

Figure 1 The prototype Timber Block "Klimablokka" made of reclaimed wood. [1]

The prototype Timber Block is now being redeveloped for production at Stavne Gård Salvage Yard in Trondheim, where work adaptation for young people is a main target. The project is partly supported by *Innovasjon Norge* (Innovation Norway) and by the municipality of Trondheim.

1.2 Stavne Gård Salvage Yard (ReBygg)

Stavne Gård Salvage Yard is part of Stavne Gård KF, that is an institution but also business related organisation owned by the municipality of Trondheim. The employees at the salvage yard have ten years of experinece, cooperating with the largest regional entrepreneurs in the process of demolishing old buildings. The participants in the work adaptation programme at Stavne Gård are trained to disassemble and take out different building components (windows, doors, roof tiles etc.), furnishings and materials that can be prepared for sales and be reused. Stavne Gård Salvage Yard is in charge of 2000 tons of waste from buildings pr. year. This is about 2% of the total building and construction waste in the Trondheim region (middle part of Norway).

1.3 Scope of research

The Stavne Timber Block project can be described as an investigation process with many aspects related to environmental and social sustainability. Climate change mitigation is met through environmentally efficient material supply and producion processes as well as through carbon storage in wood. Adaptation is pursued through a flexible building system that can adapt to various technical and functional reqirements and that also facilitate changes and salvage. Furthermore, in the production line of the block, work adaptation is an important aspect. As for the final user of the Timber Block, the project aims to design a new self-building concept.

The investigation involves a number of practical and theoretical problems. It also involves a number of stake holders. The scope of this paper is to fold out the issues related to the project and to discuss viable options for the design of the block.

Every design process is unique and in many ways it resembles a research process. The investigations of the Stavne Timber Block are informed by a comprehensive list of criteria to guide the design. Furthermore, as this is not a closed industrial development but rather an open democratic process, the decision-making is made transparent to the stake-holders. Therefore, the process requires a level of systematization and dissemination that is not common in architectural or product design. The development process is thus reported as research - or more precisely as *research by design*. Four different construction systems for the block are outlined and discussed in relation to the given criteria. The aim is to inspire and aid similar development projects based on specific, local premises.

2 SUSTAINABILITY

2.1 Environmental efficiency

Wood is generally regarded as an environmentally sound building material, and it also has a range of end-of-life options. Wood components may be reused, shredded and recycled into fibreboards and paper products or it may be burned for heat recovery.

Recycling is referred to as *down-cycling*, which indicates that a lower-grade material is produced. Down-cycling procedures often include industrial processes and long-distance transport, which demand energy and release emissions and waste. According to the “recycling hierarchy”, reuse is therefore a more preferred option because the material quality is retained at a minimal environmental cost [2]. Also, reuse is the only option that addresses carbon storage.

The production of the Stavne Timber Block can be described as an *up-cycling* process. By reusing waste material and developing a building block through product- and system-design, the material is given new functional and economic value.

2.2 Social empowerment

The project of development is based on Stavne Gård KF and their support-activites to young people for work adaptation, social training and personal develpoment. The production line and sales of the Timber Block will be important to Stavne Gård empowering the participants in their special programmes.

The building block aims for a self-building concept. Norway has a long tradition in self-building. This is an activity executed by the individual users and owners of the house. The tradition opens for exchanging knowledge about materials, construction and functions necessary to support a dwelling of comfort, and environmentally sound solutions. The self-building culture is often involving neighbours, friends and family in the building process as well.

2.3 Financial considerations

Although industrial recycling is becoming more common and is also profitable for some building materials, reuse and up-cycling of components are not commonly performed. One important reason is that the costs run high with the extra time use required.

Stavne Gård is in a special situation because the financial framework is based on work adaptation. Thus, the reuse activity can be performed at more ideal premises. In a future perspective, however, factors such as shortage of resources, environmental legislation and taxation policies may enforce more focus on reuse of materials in general. Therefore, the experiences gained today by Stavne Gård can become valuable also for enterprises operating in a building industry governed by pure market forces.

The original prototype of the Timber Block is considering the concept to be economically compatible with other building solutions of middle and high quality. Even though the production line at Stavne Gård to some degree is supported by the social working programme, the Timber Block concept must be further developed and evaluated in terms of work intensity. The goal is to establish a production line that can be cost-efficient and thus provide a building system that is economically feasible for first-time home buyers.

3 MATERIAL SUPPLY

The raw material supply is based on local and low-grade wood such as stubs and reclaimed waste (Figure 3). This material counts for approximately 17% of the total building and construction waste in Norway. The percentage is estimated to increase the next 10 years simultaneously with new prohibition against organic based waste to landfill by June 2009. The Stavne Timber Block will be produced of wood stubs and reclaimed wood from new building projects, rehabilitation and demolishing of old buildings (Figure 2).

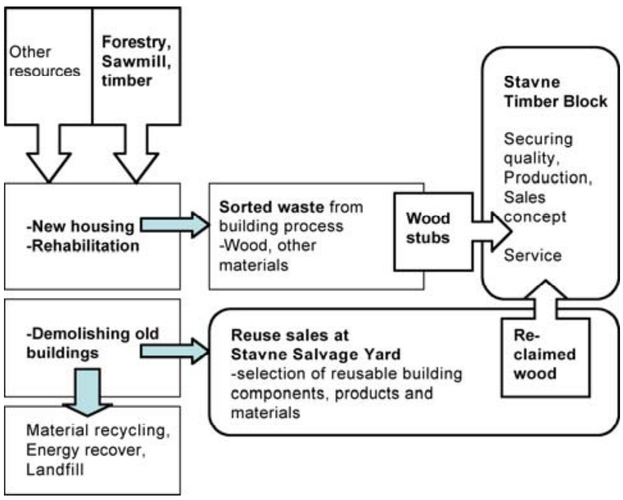

Figure 2. The production of the Stavne Timber Block integrated in local wood material loops.

Figure 3 Material supply at Franzefoss. (Photo: K. S. Wigum)

4 DESIGN CRITERIA

To reach the high ambitions regarding a full specter of sustainability targets, a comprehensive list of design criteria was worked out. As described in chapter 3, the raw material supply will be based on local and low-grade wood such as stubs and reclaimed waste. A second basic principle is to keep the environmental investments low throughout the production process. This regards energy use for processing and transport as well as choice of secondary construction materials. In addition, criteria are connected to four aspects of the block design.

The design criteria are given as general performance standards. The first aspect regards environmentally efficient use of materials in the lifecycle, or *salvageability*. The second aspect considers the various *user needs* through the lifetime of the house. The third aspect regards utilizing the specific *material properties of wood* in a best possible manner. The fourth aspect regards designing the blocks so that the *production line* and distribution systems can benefit.

4.1 Salvageability

Environmentally efficient use of materials must be pursued throughout the lifecycle, addressing:

- *Reuse and recycling.* Relevant design criteria to achieve this are: *Limited Material Selection, Durable Design, High Generality, Flexible Connections, Suitable layering* and *Information and Access.* These criteria are further detailed in [2].
- *Heat recovery.* After the components last service life, the blocks should be suitable for heat recovery in standard wood-burning stoves, without the need for flue gas cleaning.

4.2 User needs

The product must adapt to demands for design and construction, as well as for the use-phase of the house.

- *Self-building.* The blocks should facilitate self-building, which regards simplicity of building method, weight of components and safety of work. Point of sale should introduce instructions to the concept and support the idea of healthy and sustainable living, both as an urban and rural solution.
- *Adaptability.* The building system must adapt to various design needs. Also, changing life situations in use phase must be met in simple ways so that self-building is still a viable option.
- *Economy.* The blocks should facilitate economic feasible dwelling solutions. The final housing should also be a cost effective dwelling in terms of low energy demand for heating, easy maintenance and flexibility in reconstructing the building.

4.3 Material properties of wood

The development of the Stavne Timber Block aim at utilizing the specific material properties of wood in a best possible manner:

- *Indoor air quality.* Wood's capacity to regulate humidity as well as heat should be maintained, and its' thermal insulation qualities should be utilized in the construction.
- *Thermal insulation*. Preferably, the blocks should achieve existing thermal insulation standards with only a complementing layer of fibreboard sheeting and aerated cladding. For low-energy buildings, auxiliary insulation can be an option. This must be investigated through model testing.
- *Carbon storage.* The issue of carbon storage in the wood material should be maintained. This presupposes long-term management of the blocks.

Technical properties of wood such as shrinkage/ swelling capacity, moisture transport capacity, thermal insulation capacity and structural strength are variable according to the direction of the wood fibre cells. The main principles are summarized in figure 5. The properties of wood with regard to the choice of construction methods are further discussed in chapter 5.

4.4 The production line

Important design criteria are posited by the production line at Stavne Gård, where work adaptation for young people is the main objective. Also, the building process is addressed:

- *Simplicity of production.* The blocks must be suitable for uncomplicated, local production, possibly at movable plants.
- *Logistics.* The blocks should be designed with regard to ease of handling, transport and storage.

4.5 Potentials for improving the prototype

The design process is now in the phase of exploring the possibilities of the original concept in the perspective of the four areas of design criteria presented.

The prototype Timber Block is made up by cross-laid boards, fastened by wooden dowels. As wood shrinks and swells depending on the relative humidity of the ambient air, cross-laying of the boards helps achieve stabilization of the wood. The construction method is described as a stacked system, where the components are joined by plugs. Stabilization is further achieved by an exterior layer of wallboard sheeting.

Figure 4 The prototype Timber Block as a stacked construction system using plugs. [1]

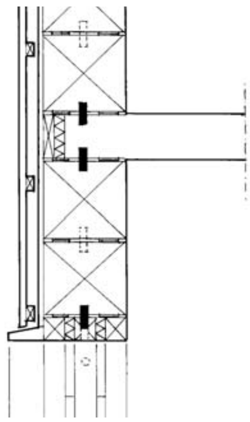

Figure 5 Sectional drawing of the prototype. [1]

After analyzing the prototype regarding the comprehensive list of design criteria, potentials for improvements were pointed out. Thus, the block was more or less taken apart and new designs emerged.

The prototype measures 374 mm each way in a cubic volume. The generality of the prototype can be improved by adapting directly to the 6M (600 mm) norm, which is implemented as an overall standard for construction materials. Secondly, smaller dimensions of the block would result in easier handling (important for both the production line and for self-building) as well as improved architectural flexibility: A smaller block could be used in a variety of constructions; both interior and exterior walls with different thermal insulation requirements. Also, a smaller block could easily be burned in standard stoves after its' last service life.

The flexibility can be further improved by choosing connection points that are visible and easily accessed. A method for joining the blocks that also allows for parallel disassembly could be investigated. Finally, a method for tagging product information - concerning manufacturer, material quality and production date - directly on the blocks could assist decision making in a potential second (or third etc.) service life.

Thus, the two main issues for the redesign are 1) smaller dimensions of the blocks and 2) flexible joints that are easily accessed. An additional desire is to design a block that also utilizes the potential for architectural articulation of the components. The lay-out of the blocks as well as the detailing of the joints can be used to support component-bound ornamentation of exposed surfaces. Addressing the architectural flexibility as well as its' inherent potential for articulation could add value to the new building system.

5 CONSTRUCTION METHODS

The two main issues for the redesign - smaller dimensions of the blocks and easily accessed flexible joints - both affect the construction in new ways, and challenges are posed. When decreasing the size of the blocks, cross-laying of boards becomes less practical. Stabilization must therefore to a greater extent be achieved in the joining of the components. After some initial sketching, the design ideas for the new block were divided in four groups, according to their constructive principles.

In the following, these four constructive principles will be discussed. Although different formats for the blocks have been proposed, a point of departure for the discussions is a block with gross measures 1x2x3 M (100x200x300 mm). This format can adapt in a number of ways to the 6M norm, and is highly flexible in meeting various architectural demands. The joining of the blocks is thus the variable input and the main issue for the discussions.

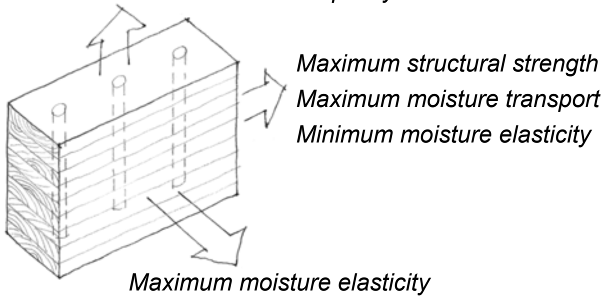

Figure 6 Proposed timber block (1x2x3 M), shown with basic technical properties, variable according to the direction of the wood fibre cells.

Technical properties of wood have been determining for the development of various vernacular building methods in wood. Aiming at using these properties cleverly in the new design, a side look to traditional building methods can be worthwhile. Also, comparisons with various contemporary building techniques, in wood as well as in other materials, can be relevant.

5.1 Node connection

The first ideas evolved around developing a type of node connection which is fully reversible and easily accessed from all sides. This would give full flexibility of the blocks which could be used to build up not only walls with different thermal insulation requirements, but also could be used in a variety of bonds to give architecturally interesting patterns.

The connection points are localized at the corners of the block. Either a tongue and groove system - as used in vernacular log constructions (Figure 7) - or separate fasteners can be specified.

Figure 7 Node connection in vernacular log construction (Photo: A.S. Nordby)

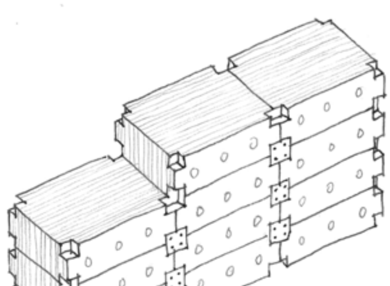

Figure 8 Node connection of the Stavne Timber Block

Although this construction alternative would optimize flexibility, the method raises some problems: The transfer of loads is depending on the precision of the blocks and joints. A high precision of the block measures can be hard to obtain as an important criterion for the production line is simple tools and operation. Also, movements of the wood caused by moisture could represent problems. Moreover, in the building process, the many node connections could result in a complicated and time-consuming construction period.

5.2 Prestress bonding

A second alternative for bonding small wood components is prestress. Rods are set in holes in the blocks and used to compress the blocks by nuts. This system would enforce stability and be less dependent of the precision of the block measures. However, it would be less flexible in construction and for later adaptations than using node connections.

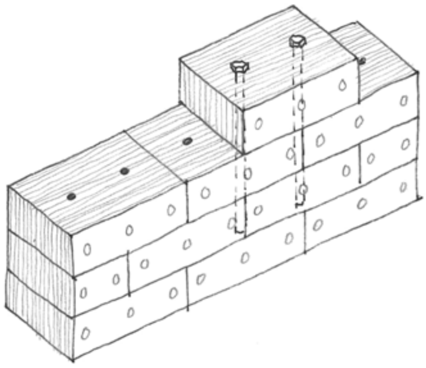

Figure 9 Pre-stress used in the Stavne Timber Block

The pre-stress bonding method could be used to connect whole walls and also sub-partitions. Furthermore, the method could be used to construct beams and columns.

Pre-stress is commonly used in concrete beams with steel rods. Steel is also commonly used in wood constructions. However, as a basic principle is to keep the environmental investments for production low, the use of steel should be avoided. Therefore, other construction materials for the rods should be considered.

5.3 Independent load bearing structure

A third alternative construction method is to separate the load bearing structure from the filling. This step would simplify the considerations regarding the structural calculations. The different constructional members could then be optimized according to the more specific requirements.

Various two-level structures in wood are known from vernacular buildings. "Stavverk", "sleppverk" and "skjelterverk" are some known Norwegian methods. In all these constructions, the structural strength in the longitudinal direction of the wood is utilized in the load-bearing members. In the infill-parts, the moisture elasticity works independently so that the movement of the wood does not disturb the structure. Rather, the movement assures tightness of the construction in different weather conditions throughout the year.

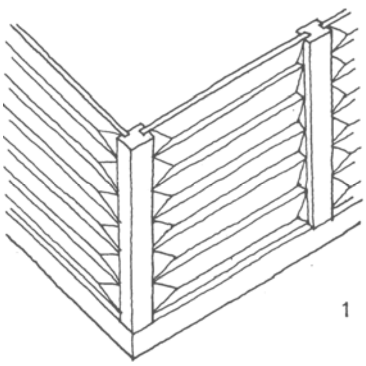

Figure 10 Vernacular "Sleppverk" (Drawing by Dag Nilsen)

The division in two separate member types could represent a more complicated production at Stavne Gård. However, it would make it easier to optimize the design according to the specific material properties of wood. Also, the infill partitions would be architecturally flexible to suit different demands.

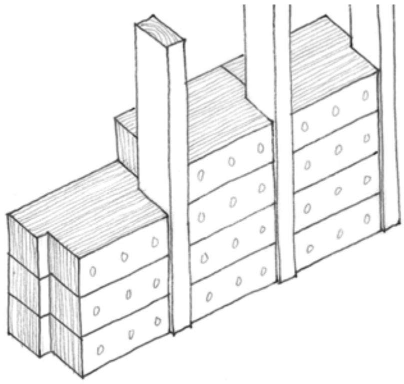

Figure 11 Load bearing members and in-fill system using the Stavne Timber Block

5.4 "Timber masonry"

The last alternative that will be discussed here is bonding of the blocks by using mortar. *Timber masonry* (or *cordwood masonry*) in various shapes is known from both vernacular buildings and from experiments performed the last 10-30 years by self-builders.

The mortar works as a bonding agent as well as a supplementary fill between the timber pieces. Clay mortar is preferred because it adapts to humidity in similar ways as wood does. Often the clay is mixed with sawdust, which may increase the homogeneity with the wood as well as the mortar's thermal insulation capacity. [3]

Figure 12 Vernacular "Log masonry" used in a barn from 1840 at Ner-Skjørstad in Oppdal, Norway. [3]

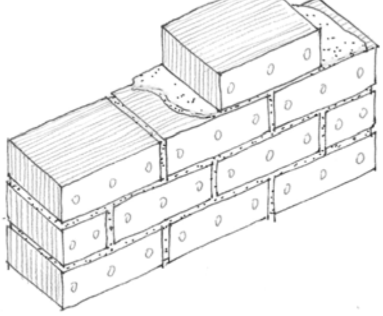

Figure 13 Timber masonry using in the Stavne Timber Block

Since wood has a higher thermal insulation capacity than clay, the mortar fillets generally represent cold bridges in the construction. Another challenge with this alternative is that the building process may be more complicated because the construction involves a second material and also - when not self-building is the case - the second profession of a bricklayer.

At the advantageous side, as the mortar works as a supplementary fill between the blocks, the precision of the block measures is not critical.

6 DISCUSSION

6.1 Material supply

The design process and research so far has shown that Norway, with a majority of wood-based housing construction, needs a variety of solutions for salvage of wood in the near future. However, building traditions from the twentieth century is not including the flexibility and easy disassembly qualities that is required for reuse. The handling of nails and metals in the reclaimed wood is a challenge both for machines and work participants. This is both an economic and time consuming barrier, as well as a question to human safety in the work situation.

6.2 Design methodology

As a part of an iterative design process, we might want to return to some basic discussions concerning the Timber Block's principle of reusing wood. To press grounded wood in blocks is an example of a totally different approach to the solution. However, in the meaning of playing along with the qualities of the wood as such, this solution is not as suitable. Every decision must however include an evaluation stage in the process regarding the design criteria set up.

6.3 Construction methods

Today, massive wood is usually provided in large-scale components that are often custom-made, and structural calculations are performed for each project. The small scale of the Timber Block, however, generally poses more complex considerations for the structure than the larger components. The block has to provide structural stability locally within each block and globally within the system. Independent of which one of the four constructive principles that will be pursued, some basic aspects must be considered:

- *The direction of the structural stress on the system.* As the structural strength of wood is significantly higher in the longitudinal direction of the cells, the system would benefit if the blocks could be stacked so that this property is utilized.
- *The wooden dowels.* The fastening of the dowels is critical for the stability of the single block. The stress on the ambient wood caused by the dowels varies according to the direction of the wood fiber cells. Also, the moisture elasticity could cause problems for the fastening in the long-term.
- *The boards.* The fastening of the boards depends on precision in production, use, structural stress as well as on moisture in the wood.

A combination of construction methods could be functional. E.g. in a two-level structure, the load-bearing members could use pre-stress bonding to assemble blocks into columns and beams, whereas in the infill parts the blocks could keep their architectural flexibility and respond to various requirements such as thermal and noise insulation, moisture transfer (particularly relevant in e.g. cow barns) as well as to different visual expressions.

7 ACKNOWLEDGMENTS

As many architects, engineers and builders have been involved in developing the ideas for the design of the new block, there is a large group of people who contributed along the way. Discussions have basically taken place informally over work desks and during breaks. The idea of designing a building component based on stubs and reclaimed waste seems to trigger creative minds. Also moral support as well as sceptical questions has been welcomed. Thanks to all who contributed in one way or the other, and in particular to Jan Siem.

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How could a Flexible and Integrated Shelter Approach Sustain the Post-Disaster Recovery?

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Abstract
The variety of contexts and the unpredictable character of post-disaster situations as well as the quickly evolving and divergent needs defining the different stages of the response stand for a serious challenge: post-disaster shelter solutions must be able to sustain these dynamics. A novel post-disaster shelter approach has been developed at the Vrije Universiteit Brussel. It relies on the conception of flexible and transformable shelter and construction systems. In order to investigate the feasibility of the presented concept, among other things, a real-scale prototype has been developed in cooperation with the Field Accommodation Unit of the Belgian Army.

Keywords:
Post-disaster shelter response; short-term versus long-term; process-based design; adaptation; transformation; up-grading; prototype testing.

1 INTRODUCTION

For a long time the sole cause of natural disasters was attributed to natural hazards – conceived as inevitable and uncontrollable physical phenomena – such as earthquakes, volcanic activity, landslides, tropical cyclones, drought, etc. Yet this conception could not explain why disasters triggered by natural hazards are killing more people over time and why the cost of disasters has risen in an accelerating manner [1], [2]. Nor could it explain the disparate and disproportionate affectation between different persons, communities and/or countries [3]. It is now clear and widely accepted that disasters have to be understood as the complex interaction between a natural hazard and the vulnerability of a community or household to the impact of that hazard. Vulnerability has a social character and is not limited to the potential physical damage or to demographic determinants only. It considers the condition of a person or group in terms of their capacity to anticipate, cope with, resist, and recover from the impact of a natural hazard; and thus the ability to adapt or adjust to changing environmental circumstances [4], [5], [6]. Factors such as poverty, population growth and urbanisation tend to increase the level of vulnerability.

2 POST-DISASTER SHELTER RESPONSE

Agencies and organisations operating in post-disaster contexts tend to describe themselves through mandates that do not overlap, in order to minimise duplication. This leads to phasing and sequential planning and support, through the different stages of the response, which is broken down into three phases – the emergency phase, the transitional phase and the reconstruction [7]. Two categories of agencies are distinguished, namely relief oriented and development oriented organisations. Traditionally, relief and development have been separate spheres of activity. The role of relief assistance is to provide urgent, short-term humanitarian assistance. It is oriented towards saving lives and alleviating human suffering. Development on the other hand is characterized by a long-term nature, concerned with sustainable capacity building and strengthening local economic, political, and social structures. [8], [9] Consequently, in almost all sectors, such as water and sanitation for example, agencies are expected to act sequentially, providing emergency relief and/or support during the reconstruction, this approach is generally also implied for shelter and housing. Still, the question remains: "what happens between relief and reconstruction?".

2.1 From emergency to reconstruction

The transitional phase is a 'grey zone' between the emergency phase and the completion of the reconstruction. During this phase people try to resume daily activities like work and school, the permanent repair of infrastructure and damaged buildings starts and actions necessary to help the community to return to normal as quickly as possible are initiated. The high cost[1] and inappropriate design of transitional shelter are often cited by its opponents, who consider the need for transitional shelter as redundant and a waste of time, material and financial means. These opponents, in many cases, prefer to opt for immediate and accelerated reconstruction. They denote the resourcefulness and coping capacity of the affected population that is estimated to be able to provide itself with shelter during the transition period from emergency to reconstruction.

[1] Different post-disaster cases have proved that the provision of current transitional shelter can be as expensive as local permanent housing, and that spending funds on temporary, transitional accommodation is likely to reduce the means available for more permanent solutions.

Nevertheless, even if the affected population can manage to provide itself with shelter, the developed settlements may lead to increased vulnerability. This was e.g. the case after the 1999 earthquake in Colombia, where the government initially didn't intend to provide transitional shelter or support transitional shelter initiatives. Yet, as a result of the formation of slums on ill-adapted sites – as the way of the population to meet the demand for shelter –, one year after the disaster the government decided to manage and provide transitional shelter and settlements. [10], [11], [12]

As Nigg (1995) states, "recovery is not merely an outcome, but rather a social process". After a disaster the affected population has lost most, if not all, of their assets. The provision of well-designed transitional shelter and settlements enables the affected population to restart a more or less normal life and can avoid the affected population from falling into a spiral of poverty and vulnerability, which would foster future disasters. Housing can take different forms and directly impacts on people's life, physical and psychological health, livelihoods, socio-economic development, etc [14], [15], [16], [17]. Beyond the physical object, the house is endowed with meaning. It is a manifestation of a personal and public symbol. The design determines the inter-relationship between the house and its inhabitants and expresses their identity.

The delimitation of space and the location of activities respond to cultural, social and personal parameters which are context-dependent and variable [14]. Within cultures there are sub-cultures and social groups, and the design and use of houses commonly reflects this diversity. Furthermore, housing has an important economic impact. It e.g. embraces the effects shelter supply has on people's productivity in the economy through the provision of a safer environment that satisfies basic needs, the consumption pattern of the household and as a productive capital in its own right as a workplace [18]. Housing and shelter thus posses important (socio-economic) developmental qualities and potentials. It is crucial to exploit these in order to at least not increase, and if possible decrease household's vulnerabilities.

2.2 Potentials and limitations of housing and shelter in post-disaster recovery

Housing plays a key role in people's lives and in society. The loss of a home does not only constitute a physical deprivation, but also loss of identity, orientation, security, privacy and dignity. When housing is destroyed in a conflict or a natural disaster, its physical loss undermines many aspects of daily life, with a profound negative effect on the community. It can cause psychological traumas, challenges perceptions of cultural identity, disrupts social structures and accepted social behaviour, poses a threat to security, and has a significant negative economic impact.

Post-disaster recovery depends on many aspects, is influenced by different disciplines and regulated on different levels. Many studies and field reports have demonstrated that physical reconstruction alone is far from enough to support effective recovery [13], [19], [20]. Yet, due to its multi-facetted character, housing has the potential to support and facilitate personal, social and economic recovery. Bolin (1985) identified a linkage between housing and mental health issues in post-disaster situations. He suggested that family recovery and the prolongation of psychosocial effects identified after a disaster are closely tied to the personal evaluation of the status of recovery and to income and home size recovery. Sheppard and Hill (2005) argue that the recovery of social capacity and economic strength are interconnected and that they should be addressed simultaneously in order to avoid the development of a culture of helplessness and dependency, a decrease in resilience and the undercutting of normal markets. Housing reconstruction is thus pivotal for the overall social and economic recovery of disaster-affected countries and communities.

However, the recovery process needs to be initiated as quickly as possible. Reconstruction – even immediate and accelerated – takes time. Most countries affected by disasters are developing countries, which face serious problems providing adequate housing to their citizens in normal circumstances. As a result, the post-disaster reconstruction is a difficult and time consuming task for the authorities of developing countries. Years may elapse before the reconstruction has occurred and daily life can resume with normality. Consequently, there is a time gap that needs to be bridged over. The provision and/or support of post-disaster transitional shelters that enable to sustain the divergent socio-economic needs and cultural habits of the affected households and community can therefore play a key role in the recovery process. Efficient post-disaster shelter response thus comprises more than providing protection from physical elements. Transitional shelter should be intended to enable people to initiate the recovery process and to get back to a more normal life. Consequently, one-fits-all, standard designs for shelter and housing reconstruction can never offer an adequate answer to the needs and aspirations of its inhabitants. Additionally, the roots of each natural disaster are to be found in the daily-life features characterising the pre-disaster context. The post-disaster reconstruction should be seen as an opportunity to investigate vulnerabilities and capacities and to take these into account during the reconstruction in order to mitigate or even avoid future disasters. The provision of transitional shelter offers the opportunity to take the time to "build back better".

3 A MORE INTEGRATED AND SUSTAINABLE DESIGN APPROACH FOR SHELTER AFTER DISASTER

Due to their short-term commitment and the relief-oriented character, but especially due to the lack of preparedness, humanitarian agencies have to make decisions that respond to the immediate situation at hand. In the chaos following the disaster, decisions have to be made quickly and often on the basis of incomplete information, resulting in ad hoc interventions that do not, in most cases, take proper account of longer-term objectives. The provision of transitional shelter occurs in the same way, relying on the delivery of standard, one-fits all shelter designs. Yet, as described in above paragraphs transitional shelter is a short-term intervention with a long-term impact on the recovery process. It is concerned with sustainable capacity building and strengthening local economic and social structures. Therefore, the design of transitional shelters must enable to support the livelihoods and socio-economic processes of the affected population.

A new conception of a flexible and integrated material support for shelter after disaster has been developed at the Department of Architectural Engineering Sciences of the Vrije Universiteit Brussel. It goes out from the design strategy Design for Deconstruction (DfD) and the 4Dimensional Design approach developed by H. Hendrickx and H. Vanwalleghem at the Vrije Universiteit Brussel. Based on this design strategy and approach, adaptable, versatile and compatible shelter systems have been conceived that make it possible to provide different types of shelters, which can evolve from a small emergency shelter to a more robust transitional shelter. The aim is to enable a quick support in the aftermath of a disaster that offers the potential to reuse the shelter material for the construction of a transitional that can be adapted, extended, transformed and upgraded with local materials by the inhabitants. The initial shelter system consists of linear structural aluminium profiles, fabric cover elements and innovative connection elements. The result can be compared with a Meccano like system that enables to configure a variety of shelter shapes, structures, sizes, etc.

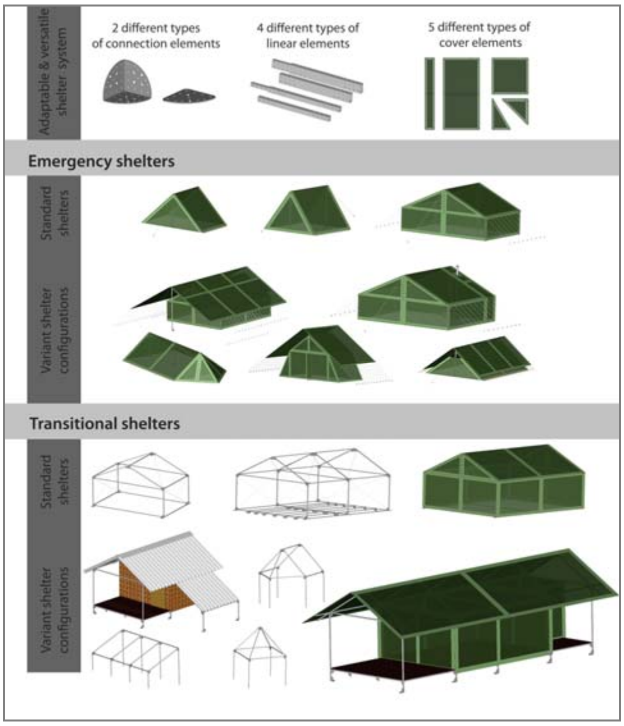

Figure 1: Scheme of the presented post-disaster shelter approach.

The key element to these transformable and reusable shelter systems are the newly developed connection elements. By means of two different types of connection elements– a flat plate and a three dimensional element – a large variety of different corner connections can be realised as illustrated in Figure 2.

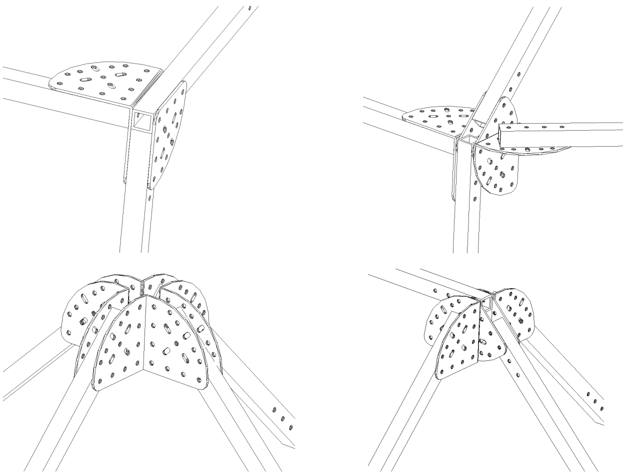

Figure 2: Potential combinations.

3.1 Increasing the preparedness and sustainability of post-disaster response

The presented design approach enables to provide a large variety of different shelter configurations. Based on a limited number of different basic elements, shelters with a varying shape, size and structural typology can be created. However, in the aftermath of a disaster decisions have to be quickly. Therefore a number of standard shelter kits have been distilled that can immediately be packed and transported to the affected area. Yet these basic shelters can be adapted to the local climate by the use of complementary 'climate kits' composed of, e.g., insulation and a complementary cover element provided with a flue plate, or shading elements and mosquito nets.

When the chaos of the emergency has passed and all affected households are provided with shelter, the emergency shelter can be dismantled and combined with additional materials to construct a more robust transit shelter.

The adaptability and the versatile character of the presented shelter and construction systems make it possible to better adapt the shelter to the needs and preferences of the inhabitants and thus to support the shelter process in a more sustainable way. By taking the broader context into account, the presented design approach aims to support the personal and economical development of the affected households by means of a flexible and adaptable material support. It therefore concentrates on an incremental, bottom-up approach that enables the inhabitants to use their own skills to construct, adapt and upgrade their shelter and reinforce their dignity. Consequently, the presented approach enables to better link relief, rehabilitation and development. Furthermore, the dismountable character of the presented approach enables to better maintain, repair, transform and upgrade the shelter. This will enable to provide more durable shelter solutions. However, the durability is only possible if the design encloses materials that are universally available and relies on simple, low-tech processing techniques, so that the elements can be repaired and reproduced locally.

3.2 Prototype tests

The feasibility of the presented concept has been investigated based on interviews, design-based research, structural analysis calculations, laboratory tests and the field testing of a real-scale prototype.

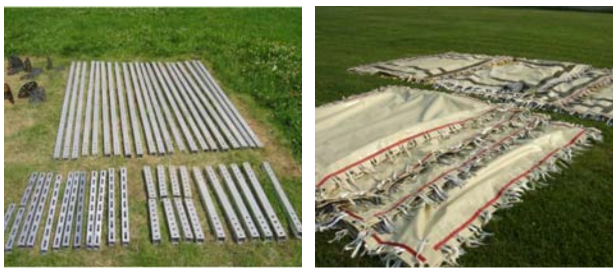

Figure 3: Elements of the shelter system prototype.

This real-scale prototype has been developed in cooperation with the Belgian Army (see Figure 3) with the scope of analysing the ease and speed of assembly, the constructability, the employability and suitability of the system, the ease of handling the elements and components, the versatility of the elements, and the adaptability of the system. In addition, the development of a prototype enabled to discover and inspect bottlenecks and to examine the design of the developed connection elements.

A quantitative as well as a qualitative analysis was pursued to investigate and evaluate the developed prototype, based on workshops that were held with different target groups among whom NGOs – Médecins Sans Frontières, Red Cross Flanders Belgium and Architecten Zonder Grenzen (Architects Without Borders) –, the Field Accommodation Unit of the Belgian Army Corps, architecture students and laymen women. By means of recording times, observations, surveys and focus group interviews better insight was gained regarding the different points of investigation mentioned above. The results complement the data that have been collected during the production and the initial testing phase.

Figure 4: Configurations assessed during the workshops.

Although some bottlenecks have been encountered during the manufacturing and testing, the results of the investigation of the first prototype are encouraging and promising. The different two-dimensional and three-dimensional frames have proved to perform very well with regard to their structural behaviour and their transformability. The tested construction system has proved to present sufficient structural integrity to withstand heavy rain, storm and wind squalls of up to 100 km/hour. Different types of shelters have been erected with a limited amount of different elements. The shelter typologies can be extended and adapted by adding and removing basic elements or by changing the combination of the elements. And at last, when assembled correctly, the shelter provides a wind and watertight indoor space. However, the prototype testing has indicated that some improvements are needed in order to guarantee an efficient implementation in the field.

The most important finding is that equilibrium has to be found between the degree of versatility, on the one hand, and the complexity and the ease of assembly on the other hand. Since one of the scopes was to investigate the flexibility and transformability of the system, the prototype was designed to be as versatile as possible. This versatility led to a wide variety of potential combinations and thus confusion, which caused some assembly errors. Some difficulties in the connection of the cover elements resulted in the set-up of a shelter that is e.g. not wind and watertight (see Figure 5).

Figure 5: Errors in the connection of the fabric cover elements.

Beside the increased complexity the large number of connection points on the cover elements – provided to guarantee water and windtight connections – dramatically increased the weight of the elements. The mass of a 1,98 x 2,56 m^2 piece of fabric, for example, amounts to 3 kg without connection elements and to 13,3 kg with the additional connection elements.

3.3 Elaboration and improvement of the presented concept

The research presented in this paper was intended to investigate the feasibility of an innovative approach for post-disaster shelter response. The scope was thus not to design a ready to use product, but more to explore the opportunities 4Dimensional Design could offer with regard to post-disaster shelter issues. It has enabled to find out the potentials and shortcomings of presented shelter and construction systems. Based on these findings the concept can be elaborated and the shelter and construction systems can be improved. The next step in the product development of the presented systems is to fine-tune the current design and investigate the economic feasibility in order to deliver a ready to use and to produce 'product'.

According to the assessment of the workshops, the constructability needs to be enhanced. The complexity and confusion related to the fabric connection points can be reduced by decreasing the amount of connection points and by using different connection techniques, depending on the function of the connection point (connection with the structure, inner layer, etc.). The use of different connection techniques for each type of connection may increase the ease of identification.

The opportunity could be provided to upgrade the construction as well as the basic elements composing the construction. For example, the upgrading and increased versatility of the fabric could be enabled by printing a model, defining the position of additional connection points, on the fabric. Further more, the amount of bolt holes and slotted holes in the connection plates should be reduced in order to minimize confusion. The position of potential holes and slotted holes could be printed or carved into the plates. The elements can then be upgraded by providing perforations in the plate at the right position.

In the search for an equilibrium between emergency needs and longer-term requirements, the weight of the shelter kit plays an important role. The different phases of the relief and recovery process are characterised by divergent and sometimes contradicting needs and requirements. During the emergency phase actions that are necessary to save lives are taken. People need help fast, especially in cold and harsh climates. The delivery time for supply is critical. The logistic requirements such as a lightweight and compact transport volume prevail. During the transitional phase actions necessary to help the community to return to normal as quickly as possible are initiated. Therefore, during the transitional phase, more robust shelter solutions, which can master time for a couple of years, are necessary. Consequently, the mass of the structure and its components may be high. In addition, in order to support the recovery process it is crucial that the transitional shelters enable to support the livelihoods and socio-economic processes of the affected population. The mass of the shelter/construction kits is related to the material chosen, the strength requirements, the versatility and the price of the shelter kit.

The structural and logistic requirements of these divergent functions and scenario's need to be examined in order to distil an integrated system made up of elements that are compatible and that can be interchanged within different configurations and scenarios. It has to be investigated how lightweight elements with a compact transport volume can be used in different structures, e.g. to reinforce more robust or larger scale structures.

At last, the shelter and construction systems should be elaborated by integrating different structural and cover materials. The motivation to implement different types of materials for the cover as well as for the structure is two-fold: it will broaden the open character of the suggested shelter/construction systems and increase the potential to combine the elements of the 'tent system' with stiff cover materials, which will ease the conversion for a temporary solution to a semi-permanent or permanent one. The integration of different materials in the presented design approach will be investigated based on case studies. The choice of the material relies on standardisation and the worldwide availability. For the structure it is suggested to examine the implementation of aluminium, steel, wood and bamboo. Due to its advantageous characteristics, bamboo is extensively used as a building material around the world for the construction of temporary as well as permanent structures. With regard to the cover fabrics, flat and corrugated plates and plywood will be analysed.

Special attention will be paid to the tolerances and play, which are necessary to guarantee the assembly and disassembly of the structures and constructions. In addition, when different materials, characterised by different features – e.g. thermal expansion –, are combined, tolerances are necessary to take the different expansions.

4 CONCLUSIONS

Due to the way in which the international community is organised, the sequential planning of the response focuses on short-term interventions meant to save lives and/or on long-term reconstruction of the build environment. However, the completion of the reconstruction takes time. What is happening between the emergency and the reconstruction? How can affected households initiate their recovery process, await for the permanent reconstruction, when they lost most, if not all, their assets? Couldn't short-term response complement long-term needs, so that the local and personal (re)development can be started as quickly as possible in order for the affected population not to cycle back in poverty and vulnerability?

Previous research has indicated that flexible and transformable shelter design is crucial to anticipate on specific and evolving, context related shelter needs and to support the dynamics of the post-disaster shelter process. The transformable character makes it possible to provide shelter solutions that better suit the socio-economic aspirations and cultural habits of the inhabitants and thus sustains the developmental opportunities shelter and housing can provide. Additionally, by enabling the reuse of shelter material over the different stages of the response, the limited material and financial means can be optimally used.

In order to investigate the proof of concept of the presented post-disaster shelter approach, among other things, a real scale prototype of a flexible and transformable construction system has been developed. The assessment of the prototype, based on workshops with different target groups, led to important findings with regard to the possibilities and limitation of transformable construction systems within the post-disaster shelter response. The overall results of the prototype testing have been encouraging. The aim to develop a transformable construction system that enables to provide different types of structurally sound, wind and watertight shelters has been reached. Nevertheless, some shortcomings with regard to an efficient field implementation have been detected. On the one hand, the aim for versatility led to a high complexity (or lack of identification) and confusion. Furthermore, the mass of the elements, especially of the cover is too high to be implemented during the emergency phase. On the other hand, the tests complementing focus group interviews made it possible to have an insight of what relief and developmental workers need and attach importance to in order to facilitate and improve the response.

The development of a real-scale prototype and its testing with different potential user groups have enabled to investigate the strong points and bottlenecks of the presented approach in order to elaborate it and fine-tune the resulting shelter and construction systems into a ready to use post-disaster shelter system.

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A Deployable Mast for Adaptable Architecture

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Abstract

Proposed here is a concept for a deployable mast with angulated scissor units, for use in adaptable temporary architectural constructions. The adaptable structure serves as a tower or truss-like mast for a temporary tensile surface structure and doubles up as an active element during the erection process. The mast consists of scissor-like elements (SLE's) which are an effective way of introducing a single D.O.F.(degree of freedom) mechanism into a structure, providing it with the necessary kinematic properties for transforming from a compact state to a larger, expanded state. The scissor units used here are not comprised of straight bars, but rather consist of angulated elements, i.e. bars having a kink angle. Although primarily intended for radially deployable closed loop structures, it is shown in this paper that angulated elements can also prove valuable for use in a linear three-dimensional scissor geometry.

Keywords:

Deployable structures, transformable structures, adaptable architecture, angulated scissor elements, kinetic architecture

1 INTRODUCTION

An innovative concept for a deployable hyperboloid mast with angulated scissor elements is presented. The scissor structure is a central vertical linear element, used to hold up several anticlastic membrane canopies at their high points. The question was raised whether it would be possible to design such a deployable mast for a temporary tensile structure and to use it as an active element during the erection process. In addition, the pantographic mast allows visitors to access several platforms to enjoy the views, under or above the different membrane elements. The proposed concept is a transformable version of the static concept shown in Figure 1. The original (undeployable) mast (or tower) consists of several modules which are assembled and dismantled on-site by stacking them vertically, for which a lifting device is needed. After assembly the membrane would have to be attached to the top, after which the pre-tension in the membrane can be introduced.

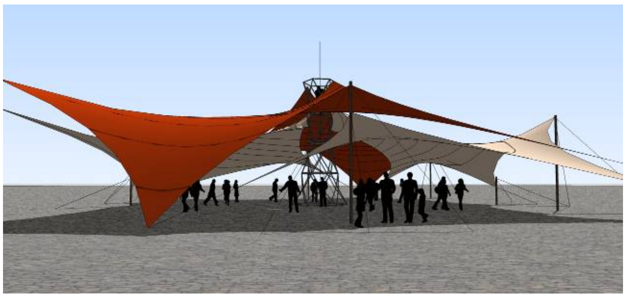


Figure 1: Mobile structure with membrane surfaces and arranged around a demountable central tower (© The Nomad Concept)

By making the mast deployable, all connections can be made on ground level, while the mechanism is in its undeployed, compact state, therefore eliminating the need for additional lifting equipment. After connections between the membrane elements and the mast have been made, the mechanism is deployed until the required height is reached and the membrane elements become tensioned. The mast could be deployed to such an extent that a sufficient amount of pre-tension is introduced in the membrane, ensuring the ability to withstand external loads. Since the mast is basically a mechanism, additional bracing is needed after full deployment to turn it into a load-bearing structure. To illustrate the concept, the simplest incarnation of the concept is used throughout the paper: a mast of triangular shape. But it must be noted that the concept is valid for any n-sided polygon. The extensive formulas for obtaining the geometry based on architectural design parameters [1] have been omitted for clarity.

2 GEOMETRY

2.1 Dimensions

The deployable mast is horizontally divided in several modules, which are closed-loop configurations of identical hoberman's units or otherwise called angulated SLE's. Figure 2 shows an example of a mast with - in this case - triangular modules, of which three are stacked vertically.

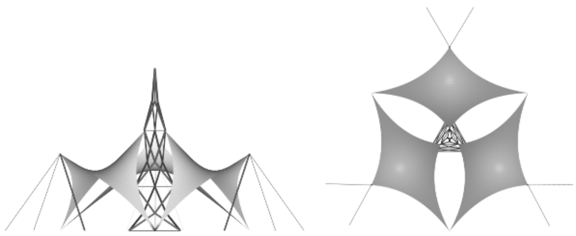


Figure 2: Side elevation and top view of the structure showing the three tensile surfaces arranged radially around the central mast

The mast is 8.5 m high and 2.7 m wide, while the tensile surfaces are identical and measure 10 m along their longest diagonal. The top of the second module, at which the membrane elements are attached, is located at 5.2 metres above ground level. The other high point of the membranes is held 4 m above ground by additional masts.

2.2 Angulated elements vs. polar elements

It could be argued that a mast with a broad base and a narrow top can equally be built with polar units with decreasing size as they are located nearer to the top. In Figure 3 two linkages – one with angulated elements, another with polar units - are shown, with identical height and width, but with varying number of units U and different bar lengths. Using the angulated elements offers an advantage: while the linkage with angulated elements is built from only 3 SLE’s with 11 hinges and nodes, the equivalent polar mechanism needs 8 units with 26 connections to reach a similar deployed geometry. The effect that the angulated elements have on the modules is that, during deployment, the top of a module becomes narrower than its base. The radius of the top of a certain module becomes equal to the radius of the base of the next, higher located module. This means that the narrowing effect is enhanced and passed on through the mechanism, from module to module, from bottom to top.

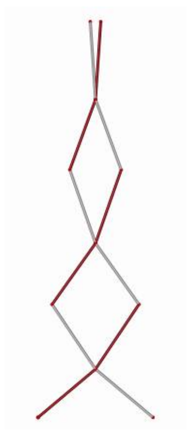
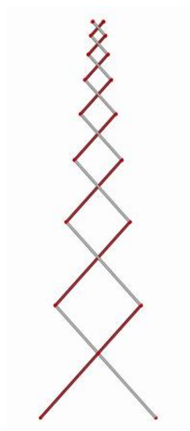
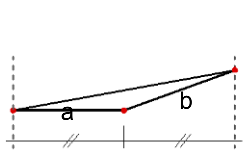
Linkage with angulated SLE’s:	Equivalent linkage with polar SLE’s:
 	 
Number of SLE’s: n=3 Number of hinges and end nodes: 11	Number of SLE’s: n=8 Number of hinges and end nodes: 26

Figure 3: Comparison between a linkage with angulated SLE’s and its conventional polar equivalent

The dimensions of the individual bars of the scissor units are such, that the horizontal projection of b is equal to a, as shown in Figure 4.



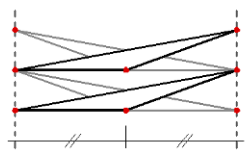


Figure 4: Imposed condition on the length of the semi-bars a and *b (a<b*), in order to make the linkage foldable along the vertical axis

The most important parameters are the kink angle *β* of the angulated element and the deployment angle *θ*, as depicted in Figure 5. The relationship between a and b, as shown in Figure 4, leads to a hyperbolic shape for the mast. By satisfying alternative relationships between a and b, a simpler, prismoid shape for the mast can be obtained, with a simpler kinematic behaviour, as later will be explained.

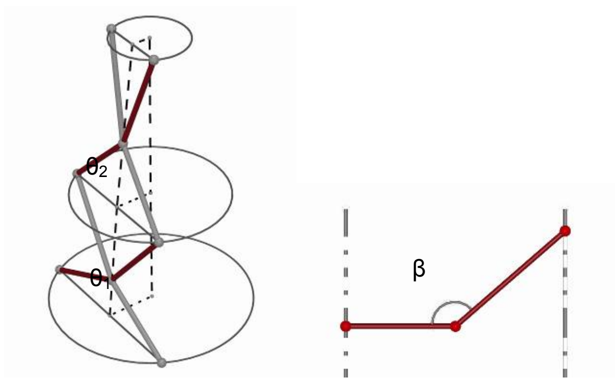


Figure 5: Most important parameters used for describing the geometry and the deployment

For a full and exhaustive description of all relevant design parameters and a comprehensive geometric design method, drawn up from the designer’s point of view, the reader is referred to [1].

3 TRANSFORMATION

3.1 Compacting for transport

The imaginary vertical axes connecting the end nodes of the bars can act as fold lines, used to further flatten the linkage. Therefore, the modules are ‘cut open’ along one fold line, after which the whole can be flatly folded for easier transport. Such a fold sequence is shown in Figure 6, which depicts the simplest possible structure: the one with a triangular base. This way of further compacting is presented as an option and could be ignored, on the condition that the dimensions in the undeployed state are kept reasonable.

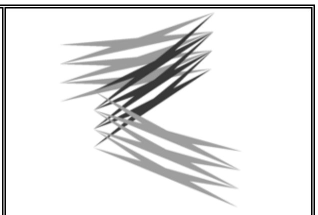
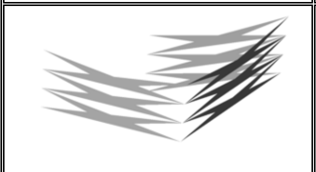
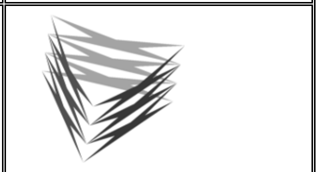
	
Step 1 (Compacted for transport)	Step 2
	
Step 3	Step 4 (ready to deploy)

Figure 6: Initial unfolding of the compacted linkage (transport) to its polygonal form (ready to deploy)

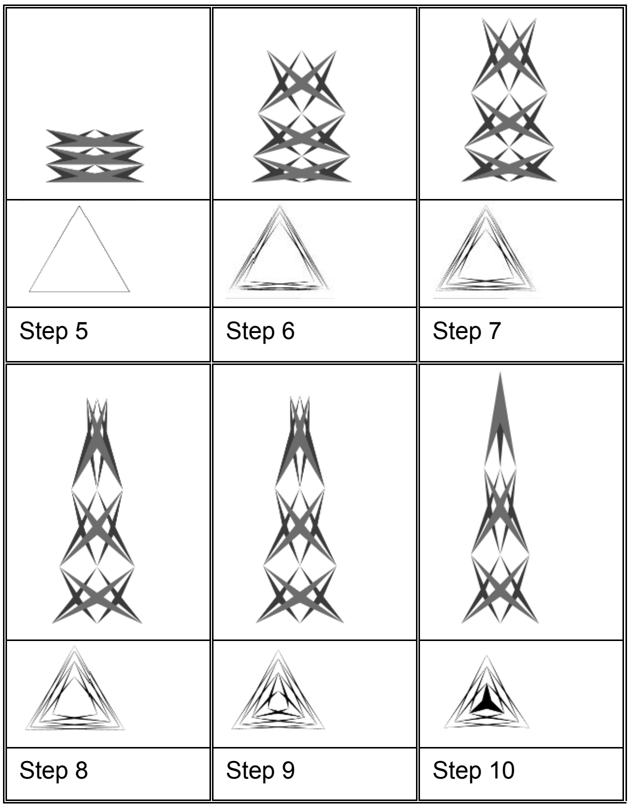


Figure 7: Six stages in the deployment of a triangular mast: elevation and top view

3.2 Deployment

The deployment sequence of the tower is presented in Figure 7, showing a top view and a side elevation for each stage. Stage 5 is the most compacted state, while stage 10 illustrates the fully deployed state. The maximum deployment is reached when the upper end nodes of the top module meet in one point.

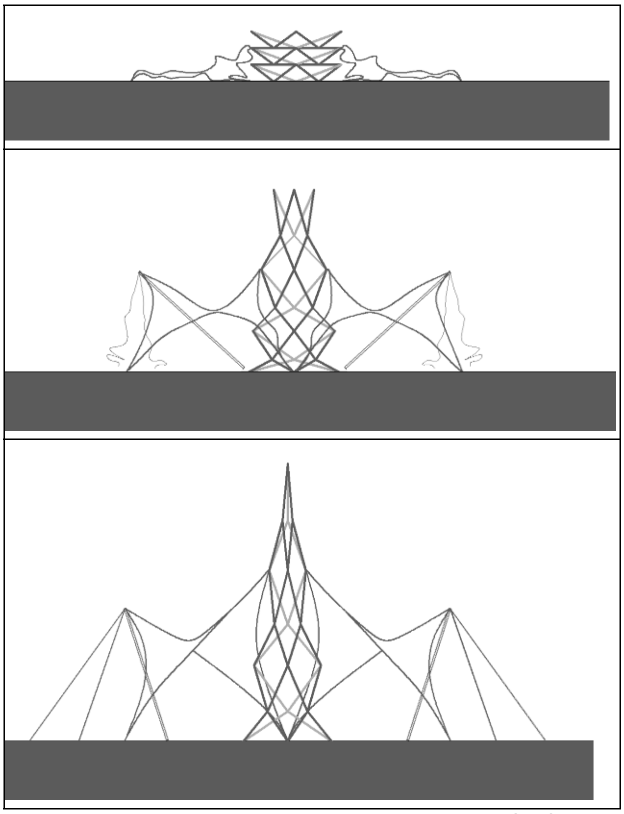


Figure 8: Deployment sequence (A, B and C) for the tower with the membrane elements attached

A short description is given of how the erection process could be executed, as shown in Figure 8:

- A: the tower is in its undeployed form. The membrane elements are attached to the nodes of the mechanism and fixed by their low points to the ground
- B: As the tower gradually deploys, the membranes are raised. When sufficient height is achieved, the additional masts are inserted and gradually put in their right location. Then, the cables fixing the secondary masts to the ground are brought under tension.
- C: Finally, the tower is slightly deployed further to add pre-tension in the membrane. Then, the tower is fixed to the ground by pinned supports and additional horizontal ties (cables or struts) can be inserted at the appropriate level.

After deployment horizontal ties are added to enhance structural stiffness. Several solutions are possible: cable ties could be used, which are already present before deployment and are shortened as the structure deploys and becomes narrower. Struts could be added afterwards to brace the structure. An active cable can run over appropriately chosen nodes along a path and can be shortened to aid in the deployment.

3.3 Influence of parameters

Minimal changes in the design values can have a profound effect on the overall geometry. The parameters with the strongest impact on the geometry are the kink angle β (as shown in Figure 5) and, logically, the number of stacked modules n in the linkage. Figure 9 shows the undeployed and fully deployed position for three different configurations with specific values for β of 135°, 150° and 165°. All configurations have the same edge length. As β increases, the overall height of the deployed configuration also increases, while the radius of the footprint decreases.

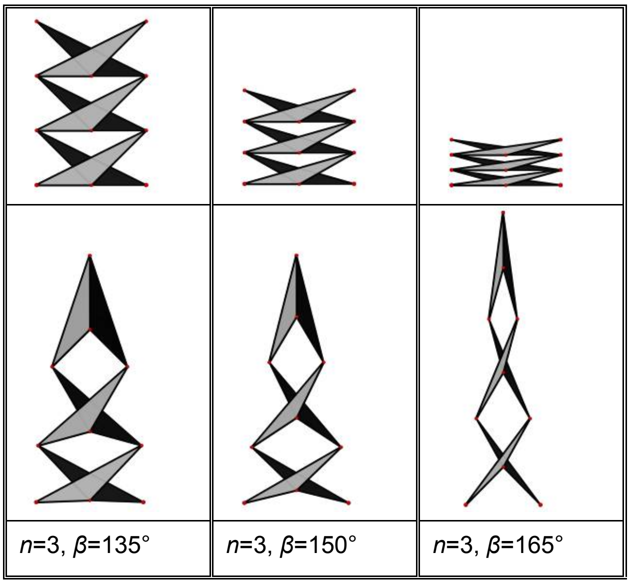


Figure 9: Illustration of the influence of the apex angle β on the geometry of a linkage with angulated SLE's with three modules (n=3) in the undeployed (top) and fully deployed configuration (below)

The biggest impact however is noticeable in the undeployed configuration. By increasing β from 135° to 165°, the height in the stacked position is reduced to a third. So blunter kink angles lead to linkages which are more compact – easier transportable - in their undeployed state.

The top module in the linkage is the determining factor for the deployment range. Units with sharp kink angles tend to quickly reach their maximal deployment, therefore halting the deployment of the remaining modules. So if a substantial expansion in height is desired, it would be a better option to choose a blunt kink angle in combination with a higher number of modules: the blunt kink angle makes the undeployed configuration more compact in height and increases the deployment interval (0 to θ_{max}). A choice will have to be made concerning the optimal number of modules that will suit the design, taking all relevant parameters into consideration.

4 KINEMATIC BEHAVIOUR

Figure 10 shows a schematic representation of an undeployed and an intermediate deployment position of the same linkage. As the deployment progresses, the angulated SLE's of each module tilt inward at the top. The dotted lines are imaginary fold lines around which mobility has to be allowed in order to complete the deployment. Through connection of the end nodes, each scissor unit can be represented by a trapezoid, of which the contour changes constantly during deployment. Between quadrilaterals ABDC and CDFE and between CDFE and EFHG there is a relative rotation which causes them not to remain coplanar

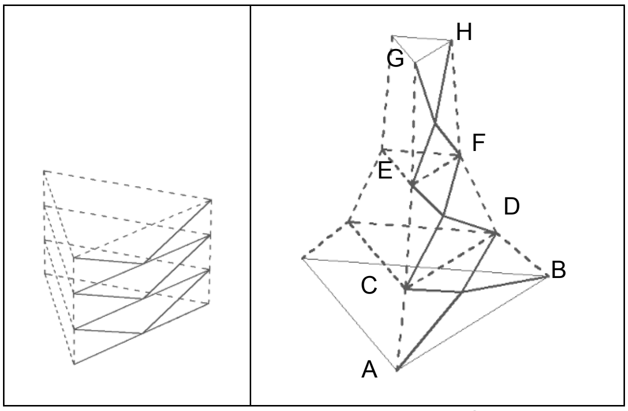


Figure 10: A schematic representation of the relative rotations of the quadrilaterals around imaginary fold axes during deployment

The joints connecting the end nodes of the units will have to take into account all aspects of this mobility. In Figure 11 and Figure 12 a proposal for such a joint is pictured, showing the seven rotational degrees of freedom needed for the deployment, as well as for the linkage to be compactly folded.

In order for the mechanism to be usable as a structure, the mobility will have to be constrained. To analyse the mobility of the system, an equivalent hinged plate model is presented in Figure 13. which represents the linkage with the rotational degree of freedom of the scissor linkage removed. After removal of this D.O.F. the remaining mobility determines to what extent constraints have to be added. Due to triangulation of the modules, there is no additional mobility which means it is basically a single D.O.F.-mechanism. Therefore, it is sufficient to constrain the movement of the rotational degree of freedom of the scissor units. As usual, fixing two appropriately chosen nodes is enough to remove the rotational D.O.F from the scissor linkage. But for using the tower as a load bearing structure, all three lower nodes have to be fixed to the ground by pinned supports. Additionally, it has been found through preliminary structural analyses, that horizontal ties - cables or struts - between the nodes greatly improve structural performance and lead to much smaller sections for the individual bars, thus enhancing the weight/height ratio [1].

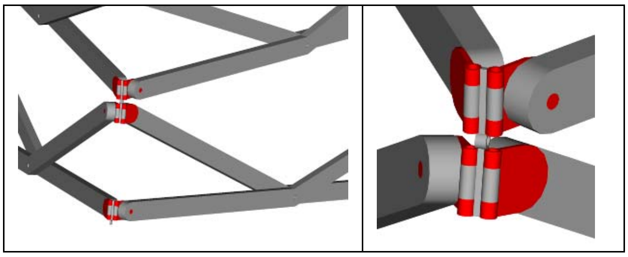


Figure 11: Kinematic joint connecting the angulated elements at their end nodes

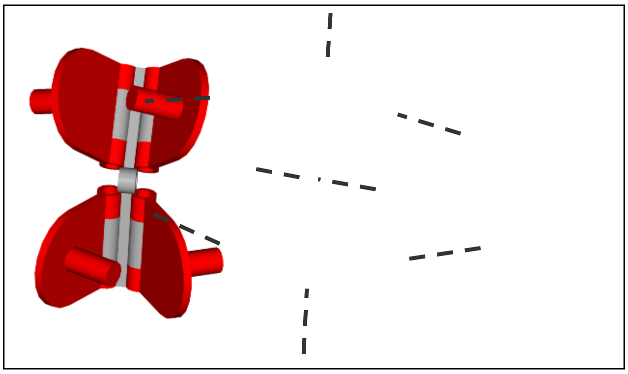


Figure 12: The kinematic joint and the axes of revolution for the seven rotational degrees of freedom

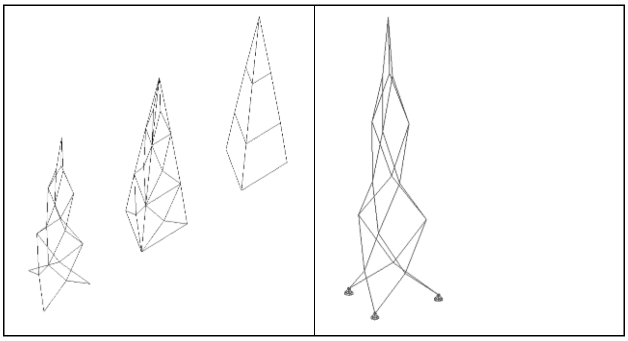


Figure 13: The scissor linkage in its deployed state and its equivalent hinged plate structure for mobility analysis (left) – Fixing the structure by pinned supports (right)

5 simplified geometry

The scissor linkage in the previously described geometry has in its undeployed state a prismatic shape and all angulated elements per vertical row (or lateral face of the prism) are coplanar. During deployment, however, the shape gradually changes into a hyperboloid, which means that the angulated elements per vertical row are no longer coplanar, i.e. they experience relative rotation, as can be seen in the triangular example of Figure 14 (left). As a consequence, the articulated hinges (Figure 12) will have to allow an extra rotational D.O.F around the horizontal axes between modules to cope with this movement, which adds to the complexity of the joint design.

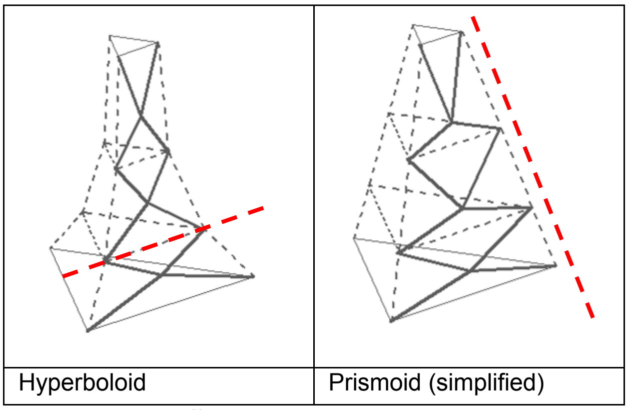


Figure 14: Difference in geometry between the hyperboloid and the prismoid version

The described deployment behaviour is caused by the particular geometry of the angulated elements, which consist of two differently sized semi-bars *a* and *b*, turning the angulated elements non-symmetrical. The overall geometry of this solution shall be referred to as *hyperboloid*.

Now, an alternative concept is proposed, which is similar in setup to the hyperboloid version, but has simplified joints for interconnecting the modules. If the angulated elements within a vertical row can be kept coplanar, then the hinges between modules would not have to allow an extra rotational D.O.F. around the horizontal axes between modules, effectively decreasing the mechanical complexity. Also, the end nodes of the angulated elements remain collinear, as shown in the triangular example of Figure 14 (right). The effect on the overall shape is that it resembles a prism before, during and after deployment. More precisely, such a shape is known in geometry as a *prismoid.*

This particular prismoid geometry can only be achieved if symmetrical angulated elements are used, i.e. elements with identical semi-lengths.

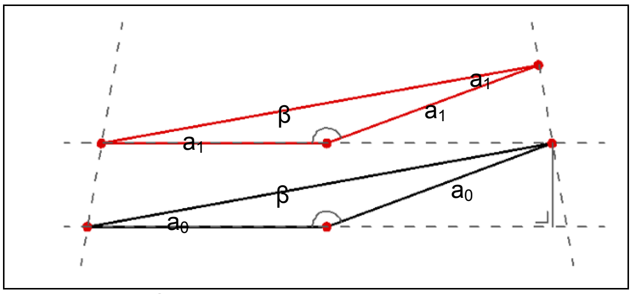


Figure 15: Symmetrical and non-identical angulated elements result in a fully compactable configuration: *prismoid solution*

Furthermore, an extra condition is imposed on the scissor geometry, as Figure 15 shows. The angulated elements become smaller near the top and their geometry is such that their lower end nodes and intermediate hinge are collinear in the undeployed position. This configuration ensures the highest degree of compactness.

The relationship between the lengths of semi-bars of consecutive angulated elements can be derived. The length of the semi-bar a_1 can be expressed in terms of a_0 as follows:

$$a_1 = a_0 \cos(\pi - \beta) \qquad (1)$$

With the kink angle β and the length of the semi-bar of the bottom most angulated element a_0 chosen as design parameters, the length semi-bar of the nth element can be written as:

$$a_n = a_0 (\cos(\pi - \beta))^n \qquad (2)$$

To illustrate what happens during deployment, Figure 16 shows the corresponding closed loop structure which uses the same vertical linkage, but arranged radially in a common plane. The planar linkage is depicted in three consecutive stages - undeployed, partially deployed and fully deployed. During deployment, a constant angle (marked by the red intersecting lines), is subtended by each vertical linkage. This characteristic is precisely what makes the design of radially deployable closed loop structures possible [3].

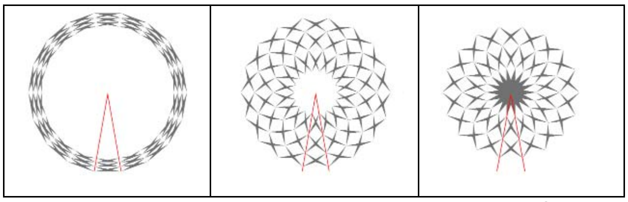


Figure 16: Three consecutive stages of the corresponding planar closed-loop structure

Figure 17 shows a three-dimensional model of a triangular prismoid tower in three deployment stages.

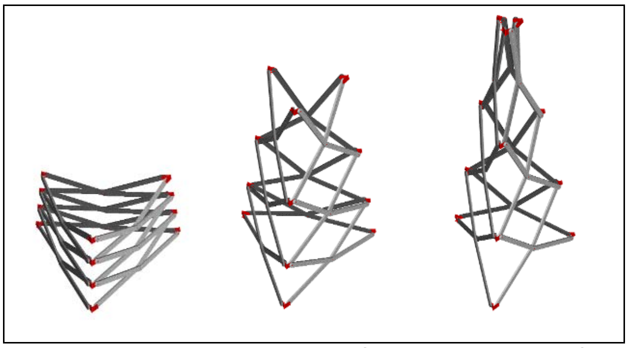


Figure 17: Perspective view of the deployment of a triangular prismoid tower

The simplified solution for the articulated hinge - which connects four bars at once - is shown in Figure 18.

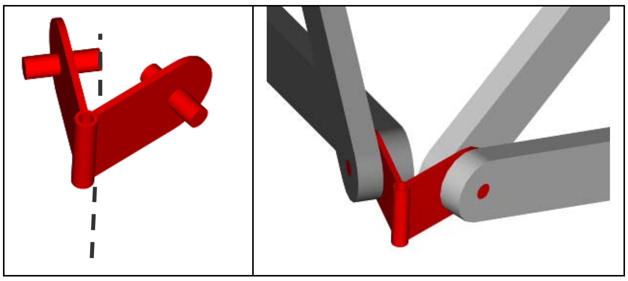


Figure 18: Detailed view of the simplified hinge connecting four scissor bars

In Figure 13, an equivalent hinged-plate structure for the hyperboloid geometry was introduced, which has shown that the only D.O.F. in the system is the rotational D.O.F. of the scissors. When the same method is applied to the prismoid solution, it can be seen that this holds no longer true. It can be concluded that the prismoid solution is – apart from the triangular geometry – a multiple D.O.F.-mechanism [1]. To turn the mechanism into a structure, and therefore removing all D.O.F.'s, all lower nodes are fixed to the ground by pinned supports.

6 FROM MODEL to realisation

6.1 1/20 scale model

In order to evaluate whether the obtained kinematic behaviour of the hyperboloid mechanism is indeed the desired one, a detailed working model has been constructed, as shown in Figure 19. This 1/20 scale model with triangular section allows the same D.O.F.'s as the full scale original and demonstrates, as expected, a single kinematic D.O.F.

Figure 19: Deployment of the 1/20 detailed scale model

6.2 1/2 scale model

The kinematic behaviour of the simplified prismoid solution has been verified by means of a ½ scale model, resulting in a 4 m high mast, as shown in Figure 20. Laminated wood was used for the angulated elements and steel for the connections. A cable-pulley system driven by an electric winch is used for the deployment.

Figure 20: Compacted and deployed state of the proof-of-concept scale model

7 SUMMARY

In this paper, a novel idea has been put forward for a deployable hyperboloid mast or tower, used for the deployment of a membrane canopy, without the need for additional lifting equipment. Angulated elements are of great use in the design of all kinds of radially retractable roof structures [3]. This concept has shown that these elements can be used in a slightly different way, i.e. in a linear mechanism. The two-fold purpose of the mast, namely holding up the membrane elements in the deployed position and serving as an active element during the erection process, has been demonstrated. It has been found that the proposed linear structure offers an advantage over existing solutions: using angulated elements instead of polar units for the same deployed geometry, has lead to a significant reduction of the number of scissor members and connections.

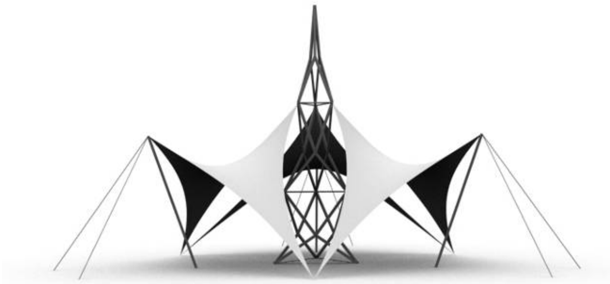


Figure 21: Rendered image of the concept : a triangular actuated mast for temporary tensile surface structures

Further, an alternative shape, called a prismoid geometry, has been proposed. This has proven to be a simpler solution compared to the hyperboloid geometry in terms of kinematic behaviour, therefore allowing the use of greatly simplified joints. Through the use of an equivalent hinged-plate model, the mobility of both the hyperboloid and prismoid geometry has been assessed. It was found that the hyperboloid configuration is always, regardless of the polygonal shape, a one-degree-of-freedom mechanism. The prismoid solution, on the other hand, is always, apart from the triangular geometry, a multiple-D.O.F.- mechanism.

The proposed concept has made innovative use of angulated scissor elements in an original application (Figure 21). Although the concept has been proven to work, more detailed analysis, including structural design of the joints, is needed.

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Adaptable Architecture with the Application of Dynamic Materials

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Abstract
This paper is part of a thesis study which focuses on the realization of an adaptable architecture with the use of dynamic materials. This research was executed based on the theory of design-driven research. The design is based on an active bending slab of material which can be implemented in an adaptable environment. Shape Memory Alloys (SMAs) and Shape Memory Polymers (SMPs) were determined as dynamic materials suitable for this design concept. SMAs can be used for actuator material responsible for deformation. SMP can be used as surface material, which has the characteristic of retaining deformation and recovery. The material properties need to be determined previous to application in a prototype. With torsion test the deformation force of the SMP was determined as well as the recovery force of the SMA under constrained recovery. The tests revealed that both dynamic materials have the characteristic to be combined in an adaptable component, which causes bend deformation.

Keywords:
Adaptable architecture, Dynamic materials, Shape Memory Alloys, Shape Memory Polymers.

1 INTRODUCTION

This paper is part of a thesis study which focuses on the realization of an adaptable architecture with the use of dynamic materials. Adaptable architecture can be described as an architecture of which its components can be adapted according to external input, such as environmental aspects and/or the behavior of the users. Dynamic materials are materials with the ability to change their physical appearance induced by external stimuli.

In literature also the term “smart” is used for adaptable components. On the architectural level adaptability is mostly examined on a structural level [2-4]. According to Wadhawan a smart structure is that “which has the ability to respond adaptively in a pre-designed useful and efficient manner to changes of environmental conditions, as also any changes in its own condition”[4]. A higher level could be reached with the use of adaptive control algorithms; the structure can become self-learning. The appliance of smart structures is mostly focusing environmental impact, e.g.; noise, light, earthquakes, wind loads etc.[5]. Over-dimensioning is avoided due to “smart” structures, which opens the way to lightweight structures.

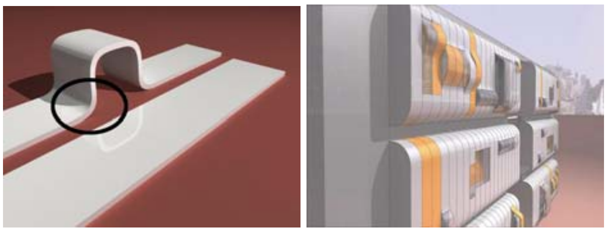
In the outfit of the building dynamic materials are also implemented; for example on the level of sun-protection. With electro chromic window technology the glass of a window can change its transparency under the influence of electric current. However, on the level of adaptability of functional aspects dynamic material implementation is lagging behind.

It will be challenging to create a building on the functional level which has the characteristic to adapt to the environment or users. Imagine the change of the size of a building or the change of the amount of rooms according to the amount of persons in the house. In urban districts the lack of space can be translated into an adaptable building which can be changed to different functions or activities. Nowadays our buildings are a static representation of a setting which has been designed in the past. As buildings have a large life-time the character of the environment of the buildings change, the actual setting of the buildings change, the function of the building changes, the inhabitants of the building change, and mostly society changes. A discrepancy between the way we live and the world surrounding us, leads to houses which are a product of the past [6].

The aim of this paper is to focus on the possibility of shape-adaptation for functional and aesthetical purposes in architectural environments. With the investigation of dynamic materials an attempt is made to assemble a prototype which will fulfill this purpose. With material testing the characteristics of the materials will be determined for the prospect of further application in a working prototype. In this paper the results of these experiments are presented.

2 DESIGN CONCEPT

This research was executed based on the theory of design-driven research [7]. In which the design, which is showed in figure 1a, will form the basis for the research. The concept is based on an actively bending slab of dynamic material which can be implemented in an adaptable environment on various ways, for example; as a facade element (figure 1b), as a ceiling element, as a space division or as a furniture element. After analyzing the design in relation to materials and techniques it was determined that the bending detail as encircled in figure 1a is the most crucial element, which needs to be studied primarily.



(a) (b)

Figure 14 a: Design bending principle of slab, b: Bending component in façade.

Based on the design concept a composite material should be appointed which contains the characteristic to bend on activation and retain this deformation without constant energy input. The material should be able to have large deformations and return to its original setting when necessary. The bending angle of the material should be controlled accurately, and a considerable amount of bending and recovering cycles should be conceivable. The deformation of the slab should be realized with small energy input. Also the materials should be able to be applied on large scale to establish application on architectural scale.

After a dynamic material inventory it was concluded that the bending component should be assembled of two materials; a surface material which has the characteristic of being flexible for bending, as well as being stiff for structural purposes and an actuator material which provide active bending properties. In figure 2 a schematic overview of the component is given.

3 EXPERIMENTS

3.1 Actuator

For the actuator material Shape Memory Alloy [8] wire was

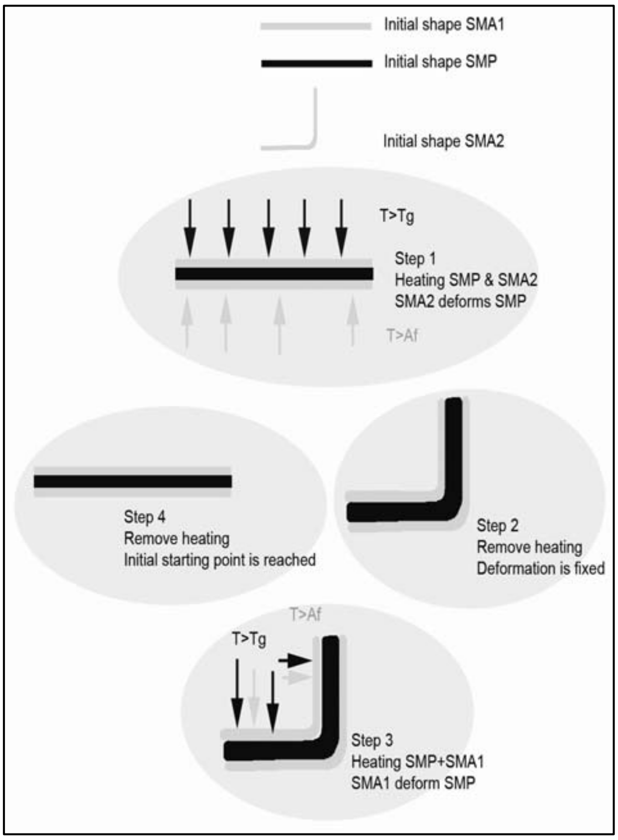


Figure 2 Schematic overview of bending component.

chosen to be the best solution for the visualization of the bending component [9]. The Shape Memory Alloy (SMA) used for this prototype is Nickel-Titanium based. SMAs have two different phases in solid state; normally around room temperature the SMA is in martensite phase, in this phase the SMA can be easily deformed. When heated, the alloy transforms into a stronger austenite phase, in which the SMA can recover to its original composition. The transformation temperature depends on the Nickel-Titanium proportion. The transformation behavior of the SMA can be seen in figure 3. SMAs have the characteristics to generate a higher recovery force under constrained recovery compared to the force needed to recover itself under free recovery. The SMA is cold worked after manufacturing, to induce the shape memory properties the Ni-Ti needs to be annealed according to specific settings.

For these experiments a wire with a diameter of 0,8 mm is employed. The 0,8 mm wire has an transformation finishing temperature (Af) of 65ºC.

Test Method annealing settings

The annealing settings need to be determined with the Differential Scanning Calorimeter (DSC) [10]. The SMA is annealed at different temperatures in a range of 450 to 650 degrees with a heating time of 10, 20 and 30 minutes. For this test the Perkin Elmer DSC 7 has been used. During DSC testing the amount of heat required to raise the temperature of a sample is compared to a reference sample. When the sample undergoes a phase transition more (endothermic) or less (exothermic) heat will be required to maintain the same temperature as the reference specimen (figure 3).

Results

Every test was cycled twice; in figure 4 it is shown that after the first cycle equilibrium is set. In figure 5 an overview is given of the DSC results with the specific heat and the temperatures. From testing with DSC it can be concluded that temperatures as low as 450 degrees do not give clear phase transition lines which is also true for temperatures above 500ºC. At temperatures around 500ºC the most optimum settings are found. A clear difference between the first time cycle for heating and cooling are found in contrast to the following cycling. After annealing SMA contains defects in the molecules lattice, like dislocations [11]. By cycling these defects stabilize.

Test method torsion

For the actuation properties of the SMA the actual amount of deformation force must be determined. In this design concept the actuator needs to deliver a bending deformation. With torsion tests the given actuation force can be determined. As the actuator has to deform a surface material, the recovery force should be determined for the SMA. With the use of a torsion testing machine, Zwick/Roell Z005, the maximum recovery torsion moment is determined. The Zwick/Roel is performed with an oven for the heating of the SMA to the austenite phase.

The test is executed with straight annealed wire. In the research of Duerig and Loughlan it is revealed that SMA loaded above an approximately strain of 6-8 % will give a controlled recovery with a considerable amount of cycling [12] [11]. Higher strains will lead to plastic deformation after which the induced strain will not be recoverable. In this experiment a straight annealed material is bended in an angle of 20º. The strain is calculated to prevent the exceeding of 8% strain. SMA is commercial available in different sizes, for this research a wire with a diameter of 0,8 mm is used. Even though the SMA has the ability to

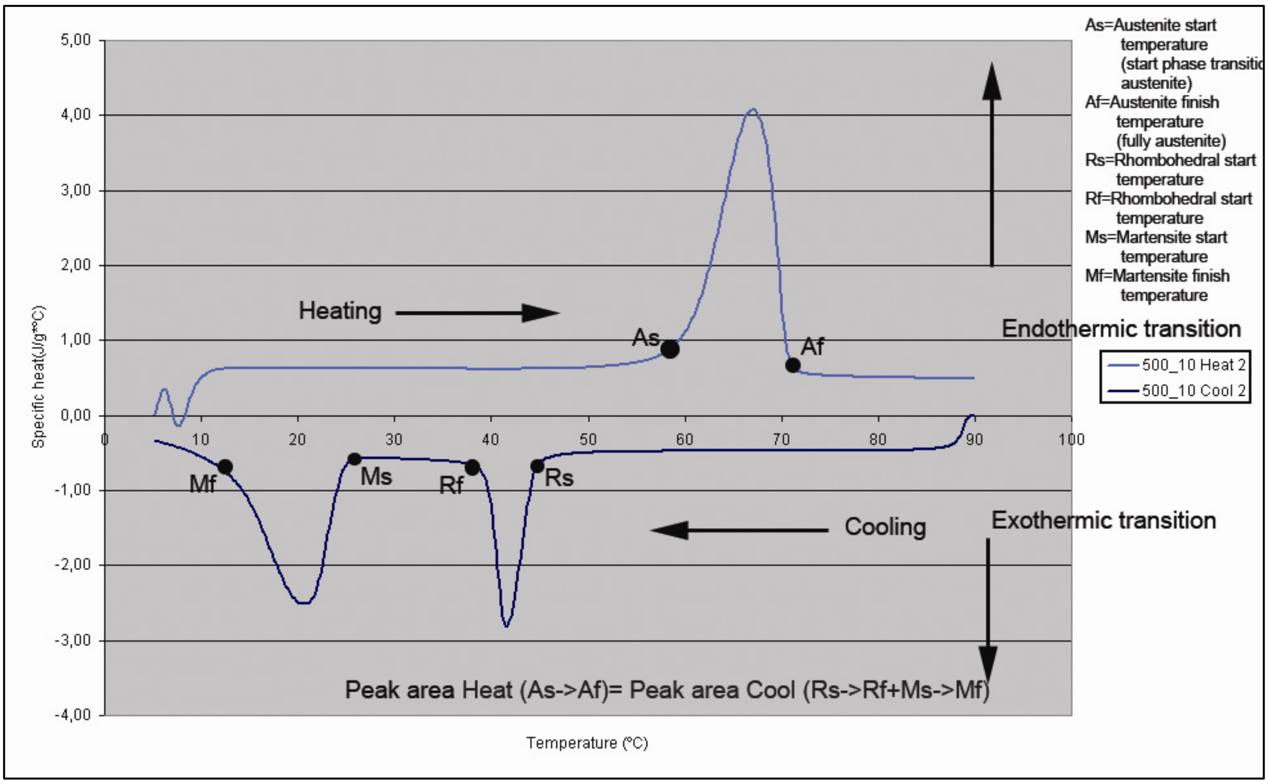


Figure 3 DSC cycle phase transition, the austenite phase transition starts at the austenite start temperature, at austenite finish the SMA is fully austenite. Between austenite and martensite the rhombohedral phase is found[1].

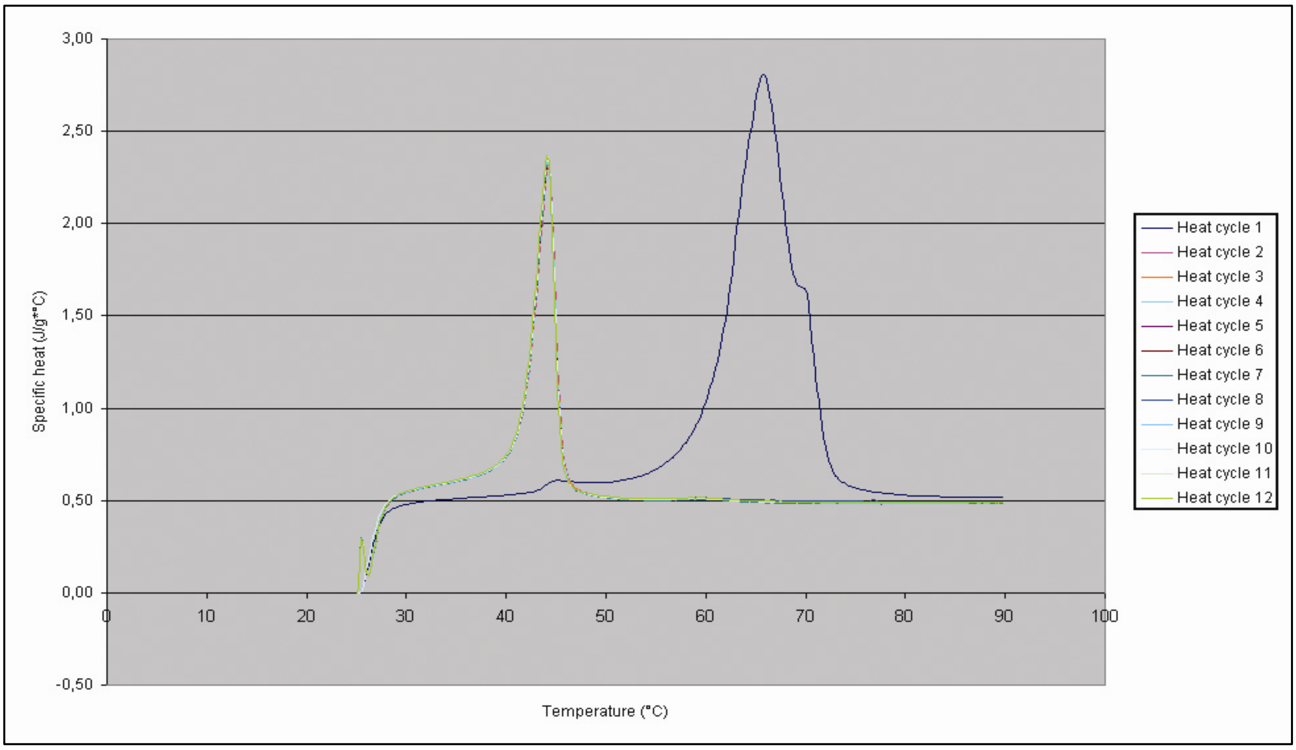


Figure 4 DSC Cycle SMA 0,49 mm.

recover under constrain, a decrease in recovery force is shown after cycling [11]. With high constrain a larger decrease in recovery force is found in contrast to unconstrained recovery. The torsion test is executed with two wires for a secure measurement. From previous research it is presented that the force capacity of the SMA actuator can be obtained by multiplying the number of wires [13]. The same test set-up is used for the SMA as is shown in figure 7 for the SMP.

The cycle was executed as followed: first in martensite phase the wires were bended in a 20° angle, subsequently the temperature was raised above the austenite finishing temperature (T=70°C), the deformation was retained to prevent recovery.

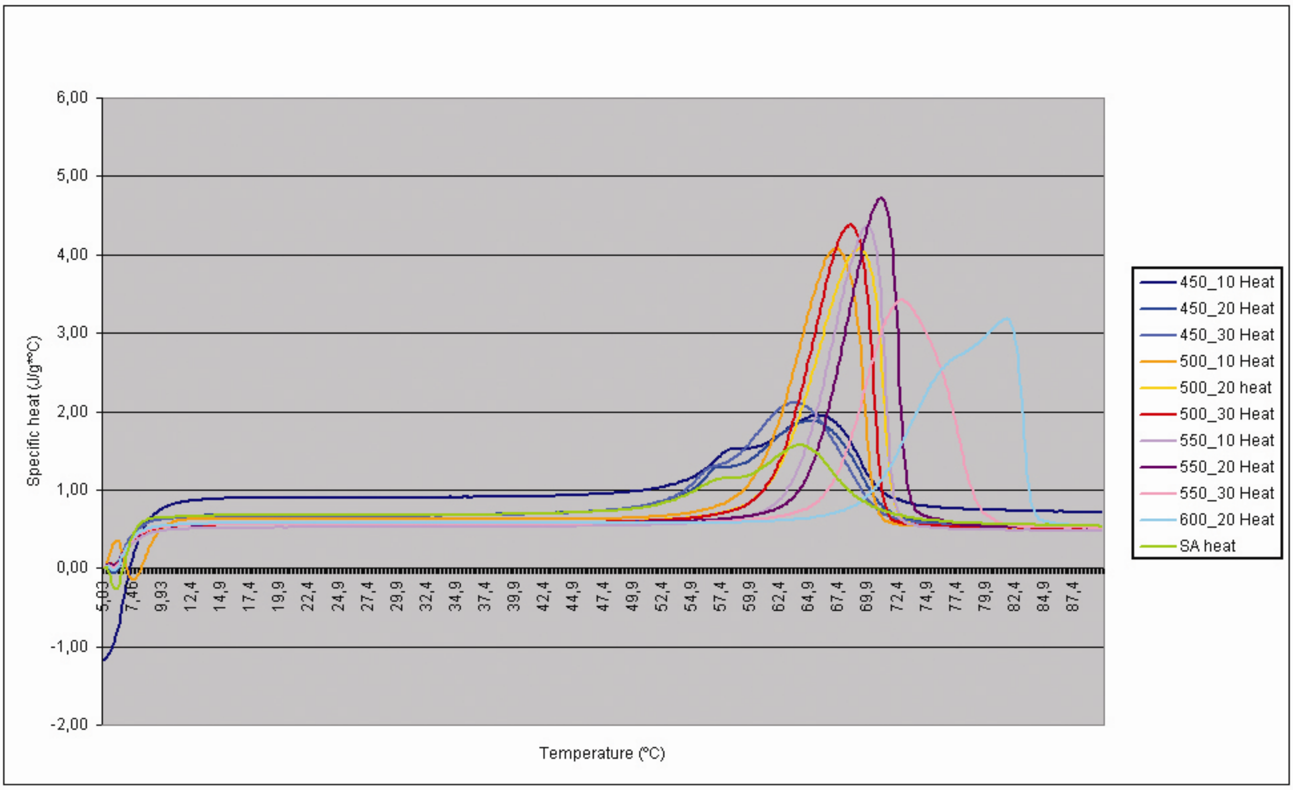


Figure 5 DSC results.

Results

Throughout the test the torsion was measured. Due to convection heating, fluctuation of the wires is caused, which leads to oscillation of the test results. An average of the torsion was calculated for martensite torsion and austenite torsion, and is shown in table 1. From the results it can be concluded that after cycle 5 the torsion settles. The difference in torsion between martensite and austenite is defined between the factor 2 and 3.

Cycle (n)	Martensite Torque torsion (Nmm)	Austenite Torque Torsion (Nmm)
1	5	18
2	4	19
3	5	20
4	11	20
5	10	20
6	10	24
7	9	23
8	9	23
9	9	24
10	9	23

Table 1 Cycling of one SMA wire in Martensite and Austenite phase.

3.2 Surface material

For the realization of the design concept (figure 1a) Shape Memory Polymer (SMP) is an appropriate material for the application as a surface material. The material can be easily deformed with small forces and can recover this deformation with low energy input. SMP has the ability to be deformed when heated above the glass transition temperature (in the case of thermoset material)[4]. SMP is in glass state [14] when the temperature is under the glass temperature (Tg), above the Tg the material becomes rubbery and easy to deform by external forces. If this force is maintained and the material cooled down under Tg, the deformation is fixed and the material regains its glass properties. When the SMP is unloaded and heated again, the SMP will return to its original position. This cycle can be repeated without degradation, the material can be elongated 200% without the

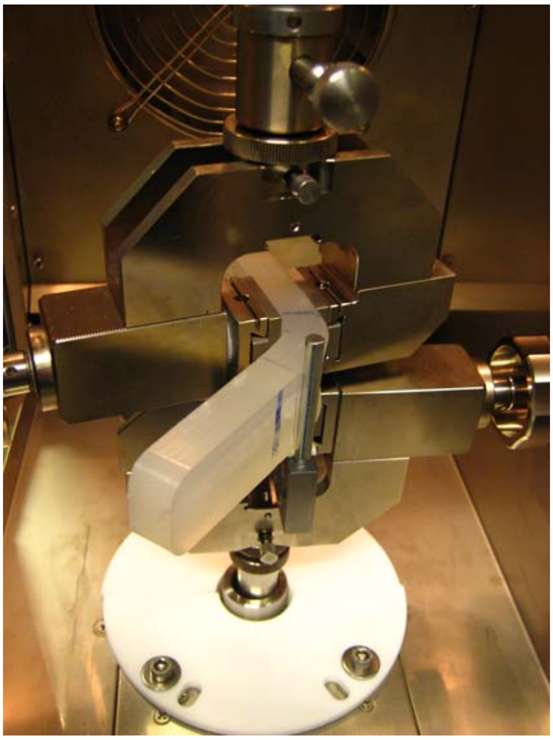


Figure 6 Test arrangement Zwick/Roel Z005 torsion testing machine

occurrence of plastic deformation [15]. In research of Tobushi the strain recovery of SMP is determined to be 98% in the case of a unconstrained recovery [16]. This is an acceptable accuracy. Furthermore, SMP can be applied on large scale with a maximum thickness of 1,3 cm[15].

Test Method deformation force SMP

For appliance in combination of SMA it is necessary to determine the deformation force. In contrast to SMA, SMP are unable to deliver a recovery stress higher than the force required for the deformation of the SMP. Torsion tests will be executed to determine the deformation force of the SMP. According to research of Tobushi et al. [17] cycling of SMP will lead to consistent deformation characteristics. After cycling, a SMP sample is bended by a torsion rate of 5º/min. Previous to deformation the environmental temperature of the sample is raised to 90ºC. Even though the Tg is determined by the manufacturer [15] at 62ºC the sample didn't become fully rubbery. The same sample is bended in angles of 20, 30 and 40º to determine whether the deformation forces related to the torsion angle. The dimensions of the sample were determined at: 5x23x44mm at which the material is clamped in the torsion test machine with 20mm. The set up of the test can be seen in figure 8.

Results

In figure 8 the outcome of the torsion test is plotted by various torsion angles. Only after an angle of 10º the torsion for the different test are found in the same data range. The maximum torsion found by 20º is 7,85 Nmm, by 30º this:12,12 Nmm and by 40º this is:15,64 Nmm. The torsion behaves linear as can be expected.

4 DISCUSSION AND CONCLUSION

These experiments can be seen as the first step to determine the characteristics of the dynamic materials for application in an adaptable composite component. Further research should be executed to determine the behaviour of the materials precisely. Based on these experiments it can be concluded that for the deformation of a SMP sample with the given dimensions in an angle of 40º a torsion of 16 Nmm is needed. The SMA wire with the diameter of 0,8 mm gives under full constrained recovery a torsion of 23 Nmm. This means that the 0,8mm wire is suitable for the deformation of the SMP. However further research should be executed on the assembly of both materials in a prototype.

During the DSC tests a clear difference between the first cycle for heating and cooling are found in contrast to the following cycles. After annealing SMA contains defects in the molecules lattice, like dislocations [11]. By cycling these defects stabilize, which can be concluded by cycling the DSC tests.

With DSC testing the temperatures around 500-550ºC gave clear graphs, however, during cooling the Rhombohedral appears, this is addressed by the fact that the SMA is annealed under the recrystallization temperature [1]. The effect of the R-phase on the shape memory effect has not been investigated in this research.

The SMA torsion test is cycled 10 times; literature reveals that after cycling equilibrium is found[11, 18]. From the torsion tests it can be clearly concluded that the phase transition of the SMA leads to a considerable raise of torsion force, this is direct related to the increase of Young modulus which is found in martensite around 30 GPa and in austenite around 75 GPa [19]. It is recommended to prevent maximum constrain of the SMA wires, this will lead to fatigue of the wires, and prevents multiple cycling [12]. Further research should examine the relation between constrained recovery and maximum cycling without fatigue

The next step in this research should be the integration of both materials for the manufacturing of the prototype on scale. Then the scaling to architectural sizes will be an important issue of concern.

5 ACKNOWLEDGEMENTS

We would like to give our gratitude to the Faculty of Chemical engineering, Mechanical engineering and Aerospace engineering for the utilization of the research labs. We also extend our sincere thank to the Young Wild Ideas Award of the Delft Centre of Materials, for the sponsoring of the materials.

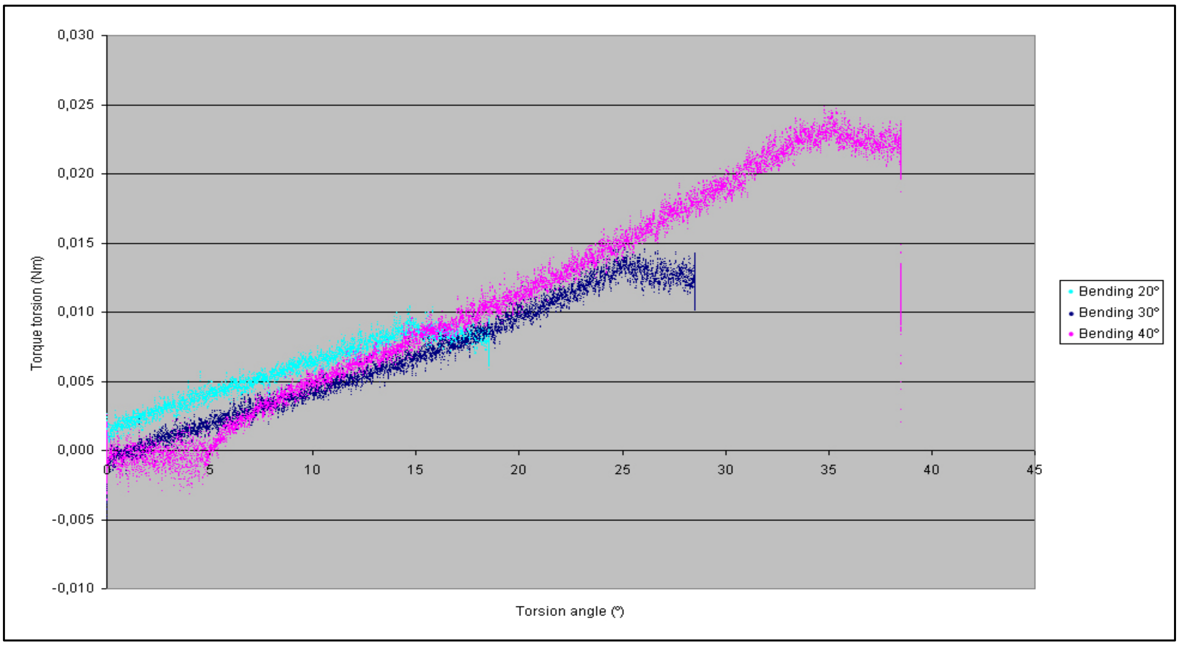


Figure 7 Relation torsion and angle

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Barriers for Deconstruction and Recycling of the Currently Built Single Detached Houses

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Abstract

The whole deconstruction processes of 16 single detached houses were recorded in detail. The 16 houses included timber post and beam houses, two by four houses, steel framed houses and a prefabricated steel unit house. Most of them were dismantled and two of them, the timber post and beam house and the prefabricated steel unit house, were deconstructed. The amount of the workers, the types and amount of the waste and the logistics of the waste were recorded to create a database. And all undesirable designs for deconstruction were listed up.

Keywords:

Dismantling, Deconstruction, Single Detached House, Waste, Design

1 INTRODUCTION

The currently built single detached houses are significantly difficult to deconstruct and the waste generated during the dismantling process have low potential to be recycled as raw materials to reproduce building materials or other products. To make effective feedback loops of the building materials it is quite necessary to design houses that can be easily deconstructed. And we should precisely know what is ongoing on the deconstruction or dismantle sites to get useful design ideas.

Some designing idea has been proposed [1][2] to make wooden houses easy to deconstruct but buildings and houses are still not designed considering the deconstruction phase. By improving the design of the buildings we can reduce the tasks on the deconstruction site and improve the recycle ratio of waste.

The dismantling process of the 16 single detached houses were carefully investigated and recorded. The result of the investigation was formed as a database. And also the undesirable design for deconstruction was listed up.

2 INVESTIGATion

2.1 Houses in investigation

The whole dismantling or deconstruction process of 16 demonstration houses was recorded during their dismantling or deconstruction process. The construction methods, floor area and numbers of stories are of these houses are summarized in Table 1.

The 16 houses include five post and beam houses, three 2X4 houses, one wood panel house and seven steel frame houses. Most of the houses were dismantled by using dismantling machines. One of the post and beam houses was deconstructed carefully by hand and rebuilt on a different site. And on of the steel houses was divided into several pieces of units and the units were carried to a

	Construction Type	Number of Stories	Floor Area (m2)	Dismantled/ Deconstructed	Days Spent for Dismantle/ Deconstruction	Necessary Works (Man x Hour)
House A	Post and Beam Construction	2	249.25	Dismantled	13	544
House B	Post and Beam Construction	2	330.17	Dismantled	17	748
House C	Post and Beam Construction	2	221.51	Dismantled	15	504
House D	Post and Beam Construction	2	239.37	Dismantled	15	476
House E	2X4 Construction	3	254.48	Dismantled	19	689
House F	2X4 Construction	2	191.19	Dismantled	12	334
House G	2X4 Construction	2	228.84	Dismantled	9	526
House H	Wooden Panel Construction	2	239.38	Dismantled	14	422
House I	Steel Construction	3	188.11	Dismantled	18	828
House J	Steel Construction	3	182.43	Dismantled	16	673
House K	Steel Construction	2	258.99	Dismantled	17	553
House L	Steel Construction	2	278.16	Dismantled	13	423
House M	Steel Construction	2	273.53	Dismantled	16	785
House N	Steel Construction	2	256.13	Dismantled	17	564
House O	Post and Beam Construction	2	253.38	Deconstructed	32	923
House P	Steel Construction	2	234.47	Deconstructed	16	533

Table 1 : Summaries of the house being dismantled or deconstructed.

different site and rebuilt.

The floor area of the houses in investigation was around 250m^2 and this is rather larger than the floor area of the normally built single detached houses in Japan. And as the houses in investigation were demonstration houses the water supply system and the gas supply system were not installed. These are the difference between the normally dwelled houses and the demonstration houses.

2.2 Record keeping on site

The record of the whole dismantling or deconstruction process of the 16 houses was kept on site. The dismantling or deconstruction works were recorded every 30 minutes. And the numbers of the workers being involved in each dismantling or deconstruction works were counted and recorded.

Every dismantling works recorded was categorized into the three layers of items listed in Table 2. The dismantling works were roughly divided into 4 main items. And each main item was divided into several sub items and again the sub items were divided into several detail items.

2.3 Collection of waste declarer documents

The waste declarer documents of some of the investigated houses were collected. The waste declare document gives information on the types and amount of the waste generated from the dismantling site. It also gives information on the distribution of the waste and the final processing methods of the waste.

3 DATABASE

3.1 Dismantling and deconstruction works

The records kept on the dismantling and deconstruction site were formed into a database. In the process of forming a database the dismantling works were categorized into 6 groups. The 6 groups are as follows:

Item	Sub Item	Detail Item	Category Group
Hand works	Curing	Setting curing sheets and scaffold	Preparation works
		Removing curing sheets and scaffold	Preparation works
	Removing furniture	Carrying out and loading	Loading
	Removing facilities	Dismantling	Dismantling
		Carrying out and loading	Loading
	Removing doors and windows	Dismantling	Dismantling
		Carrying out and loading	Loading
	Removing flooring materials	Dismantling	Dismantling
		Carrying out and loading	Loading
	Removing fixed furniture	Dismantling	Dismantling
		Carrying out and loading	Loading
	Removing interior finish	Dismantling	Dismantling
		Carrying out and loading	Loading
	Removing interior fittings	Dismantling	Dismantling
		Carrying out and loading	Loading
	Removing gypsum boards	Dismantling	Dismantling
		Carrying out and loading	Loading
	Removing interior framings	Dismantling	Dismantling
		Carrying out and loading	Loading
	Removing insulation	Dismantling	Dismantling
		Carrying out and loading	Loading
	Removing exterior finish	Dismantling	Dismantling
		Carrying out and loading	Loading
	Removing roofing materials	Dismantling	Dismantling
		Carrying out and loading	Loading
	Removing exterior fittings	Dismantling	Dismantling
		Carrying out and loading	Loading
	Removing plants	Removing	Other Works
		Loading	Loading
Machine works	Preparation works	Setting steel plates for curing	Preparation works
		Removing steel plates	Preparation works
		Moving building materials	Preparation works
		Transportation and setting of dismantling machine	Preparation works
		Adjustment of dismantling machine	Preparation works
		Fueling	Preparation works
	Dismantling Building	Dismantling buildings	Dismantling
		Separation of the waste	Separation and selection
		Moving the waste	Separation and selection
		Loading the waste	Loading
		Water sprinkling by hand	Dismantling
		Separation of the waste assisted by hand	Separation and selection
		Loading the waste assisted by hand	Loading
	Dismantling Foundation	Dismantling foundation by machine	Dismantling
		Separation of the waste by machine	Separation and selection
		Loading the waste by machine	Loading
		Dismantling foundation assisted by hand	Dismantling
		Separation of the waste assisted by hand	Separation and selection
	Leveling of Ground	Leveling of ground by machine	Other Works
		Leveling of ground by hand	Other Works
	Removing Plantings	Removing plants	Other Works
		Loading plants	Loading
Transportation	Transportation	Arranging the bed of the truck/Taking photo	Other Works
		Filling up the declarer sheet	Other Works
		Transportation	Transportation
	Preparation works	Loading and unloading the container	Preparation works
		Truck washing	Preparation works
Other works	-	Cleaning	Other Works
		Consultation	Other Works
		Break	Other Works
		Waiting	Other Works
		Preparation works	Preparation works
		Instruction	Other Works

Table 2 : Items and category groups of the dismantling works.

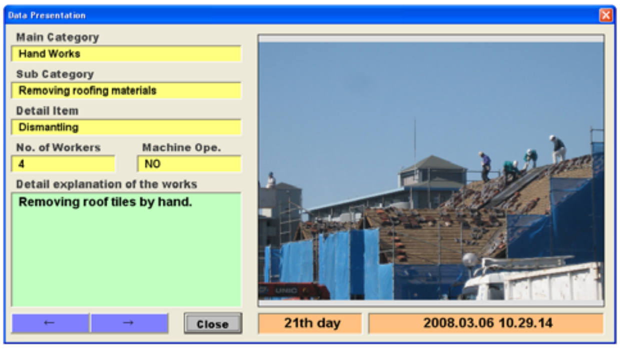


Figure 1 : Data veiw window.

Group 1: Dismantling / deconstruction

Group 2: Separation and selection

Group 3: Loading

Group 4: Preparation works

Group 5: Transportation

Group 6: Other works

A tool was prepared to view and analyze the data. Figure 1 shows an example of the data view windows. The information given in the data view windows are as follows:

(1) The main items.

(2) The sub items.

(3) The detail items.

(4) Detail explanation of the works.

(5) The number of workers.

(6) Usage of machine operation.

(7) Date and time.

(8) Representative photograph.

Figure 2 shows an example of the data analyzing windows. The subtotal of the works consumed in a certain dismantling or deconstruction work can be calculated for each main items, sub items and detail items. And the works consumed in each category group and the machine operating hours can also be calculated.

3.2 Waste

The data of the types and amount of the waste generated from the dismantling site were collected by analyzing the waste declare documents. The types of the waste generated during the dismantling process are as follows:

(1) Concrete

(2) Concrete, tiles and other inorganic materials

(3) Glass and ceramics

(4) Gypsum board

(5) Steel and metal

(6) Plastics

(7) Wood

(8) Fiber

(9) Paper

(10) Mixed waste

In most cases the amount of the waste was measured in volume. The volume of the waste was converted to weight by using the following equation.

$$Weight = Volume \times Densty \quad (1)$$

Where,

Weight is the weight of the waste (ton)

Volume is the volume of the waste (m^3)

Density is the density of the waste.

The values of the density [3] applied in the calculation are summarized as follows:

(1) Concrete: 1.1

(2) Concrete, tiles and other inorganic materials: 1.1

(3) Glass and ceramics: 0.6

(4) Gypsum board: 0.4

(5) Steel and metal: 0.7

(6) Plastics: 0.1

(7) Wood: 0.2

(8) Fiber: 0.1

(9) Paper: 0.1

(10) Mixed waste: 0.3

4 result AND DISCUSSION

4.1 Analysis of Works

4.1.1 Dismantling Works

One result of the analysis of the dismantling works is given in Figure 3. Figure 3 shows the results of House A and it gives the detail sketch of the time

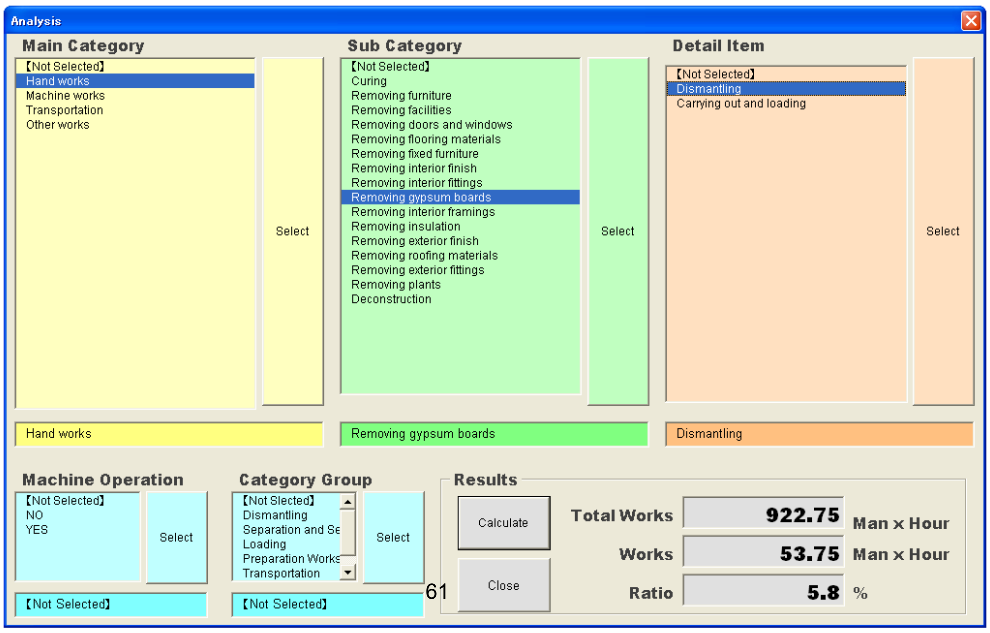
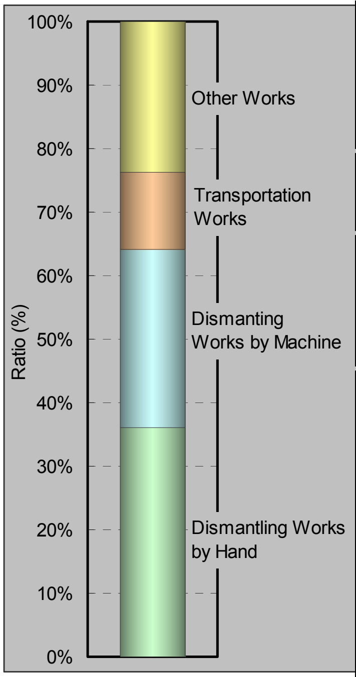


Figure 2 : Data analyzing window.

and task consumed during the dismantling process.



Other Works	Labor Consumed (Man x Hour)
Cleaning	16.8
Consulation	5.5
Break	90.5
Waiting	8.0
Preparation	8.5
Instruction	0.0

Transportation Works	Labor Consumed (Man x Hour)
Transportation	66.0
Preparation	0.0

Types of Machine Dismantling Works	Labor Consumed (Man x Hour)
Preparation	7.5
Dismantling Building	113.0
Dismantling Foundation	27.8
Leveling of Ground	3.5
Removing Plantings	0.8

Types of Hand Dismantling Works	Labor Consumed (Man x Hour)
Curing	22.0
Removing Furniture	33.0
Removing Facilities	24.5
Removing Doors and Windows	7.3
Removing Flooring Materials	0.0
Removing Fixed Furniture	9.5
Removing Interior Finish	0.0
Removing Interior Fittings	2.3
Removing Gypsum Boards	56.0
Removing Interior Framings	0.5
Removing Insulation	7.3
Removing Exterior Finish	3.5
Removing Roofing Materials	30.5
Removing Exterior Fittings	0.0

Figure 3: Result of the analysis of the dismantling works (House A).

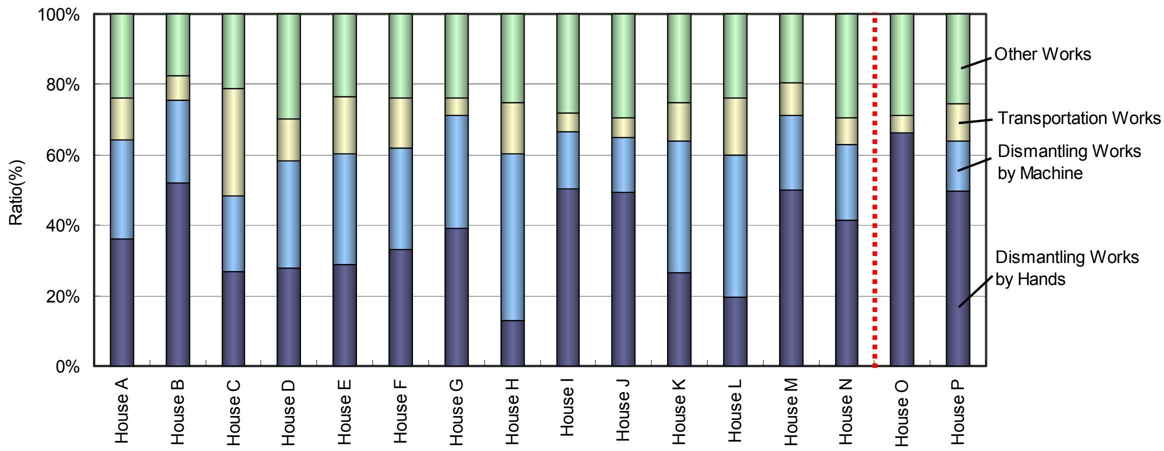


Figure 4: Summary of the analysis of the dismantling works.

Figure 4 gives the summarized results of the dismantling works of the 14 houses being dismantled and the 2 houses being deconstructed. There are roughly two processes in the dismantling works. One is the process to remove finishing materials, joineries, fittings, gypsum boards, roof tiles and insulation materials from the skeleton of the house by hand. In this paper this process will be call as “Hand Dismantling”. And another process is the process to pull down the skeleton of the house by machine. In this paper this process will be called as “Machine Dismantling”.

In average almost 40% of the dismantling works were consumed in the hand dismantling process and almost 25% of the dismantling works were consumed in the machine dismantling process. The ratio of the works consumed in these two dismantling processes differed among the construction types. In average the ratio of the hand dismantling works was calculated as 57% for the post and beam construction, 48% for the 2X4 construction and 21% for the wood panel construction.

And ratio of the hand dismantling works was calculated as 72% for the group of steel framed houses I, J, M and N and 37% for the group of the steel framed houses L and M. The difference between these two groups was that the former group was rather carefully dismantled than the latter group.

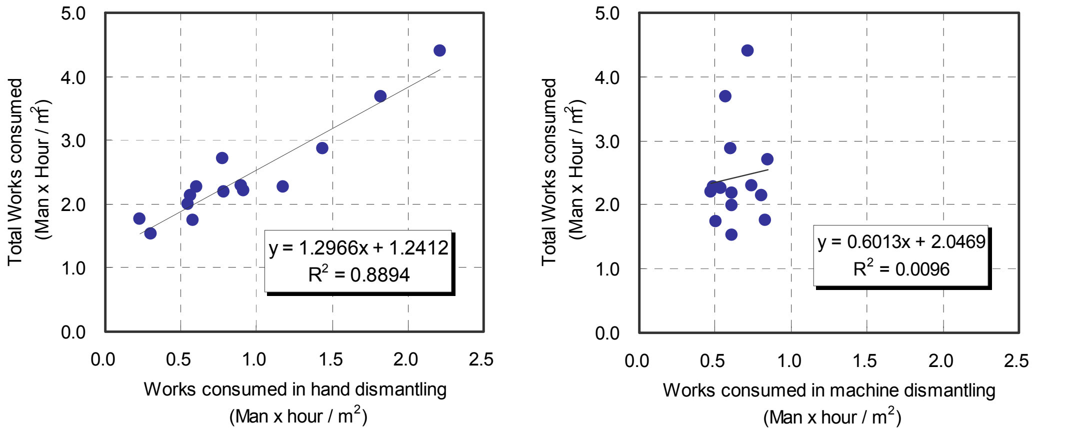
The amount of the works consumed in dismantling a unit area is summarized in Table 3. The works consumed in dismantling the unit area was 2.18 for the post and beam construction, 2.25 for the 2X4 construction, 1.76 for the wood panel construction and 2.80 for the steel framed construction.

In general the total amount of the dismantling works was affected by the amount of the works consumed in the hand dismantling process. Figure 5(a) shows the relationship between the total dismantling works and the hand dismantling works. And Figure 5(b) shows the relationship between the total dismantling works and the machine dismantling works. The total dismantling works and the hand dismantling works have a good correlation but the total dismantling works and the machine dismantling works seems to have no good correlation.

4.1.2 Transportation and other works

In average 15% of the works was consumed in the transportation process and 25% was consumed in the other activities such as coffee break, lunch and meeting.

4.1.3 Works consumed in category groups



(a) Hand dismantling works

(b) Machine dismantling works

Figure 5: Relationship between the total dismantling works and the hand or machine dismantling works.

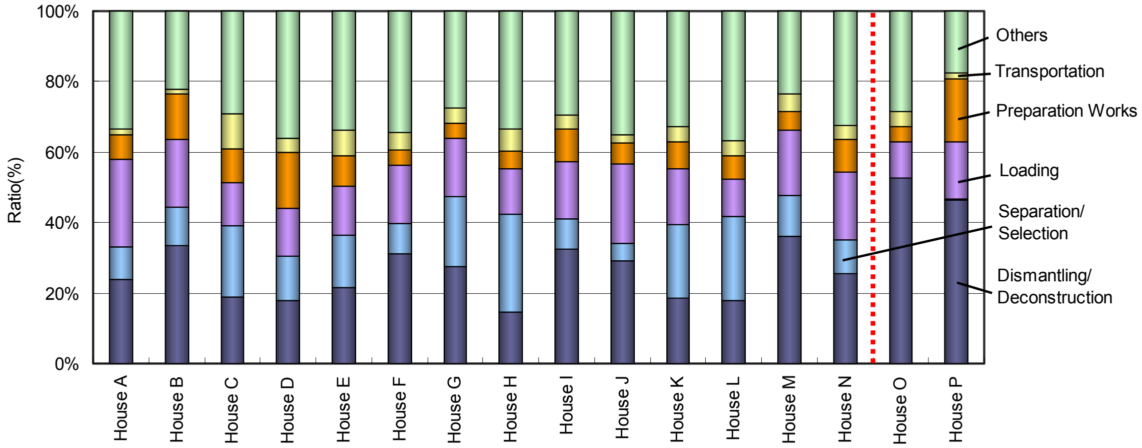


Figure 6: Works consumed in each category group.

Construction Type	Name	Unit Dismantling Work (Man x Time / m^2)	
Post and Beam	House A	2.18	2.18
	House B	2.26	
	House C	2.27	
	House D	1.99	
Two by four	House E	2.71	2.25
	House F	1.75	
	House G	2.30	
Wood Panel	House H	1.76	1.76
Steel Framed	House I	4.40	2.80
	House J	3.69	
	House K	2.14	
	House L	1.52	
	House M	2.87	
	House N	2.20	
Post and Beam	House O	3.64	3.64
Steel Framed	House P	2.27	2.27

Table 3: Works consumed in dismanlting or deconstructing a unit floor area.

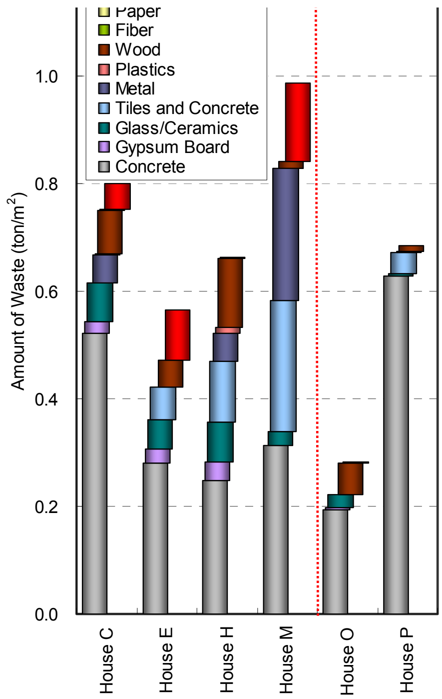


Figure 7: Types and amount of waste.

The dismantling works were grouped in to 6 category groups as shown in Table2. The works consumed for each category group are calculated and summarized in Figure 6. In average 26% of the works was consumed in the dismantling or deconstruction process. And 14% was consumed in the separation and selection process, 17% in the loading process, 8% in the preparation process and 4% in the transportation process. The rest 31% was spent for the coffee break, meeting and standby.

4.2 Waste

Figure 7 shows the types and amount of the waste generated from the deconstruction site for some of the representative house. The figure shows the weight generated from a unit floor area of the following houses:

(1) House C: Post and beam construction
(2) House E: 2X4 construction
(3) House H: Wood panel construction
(4) House M: Steel framed construction
(5) House O: Post and beam construction (Reused)
(6) House P: Steel framed construction (Reused)

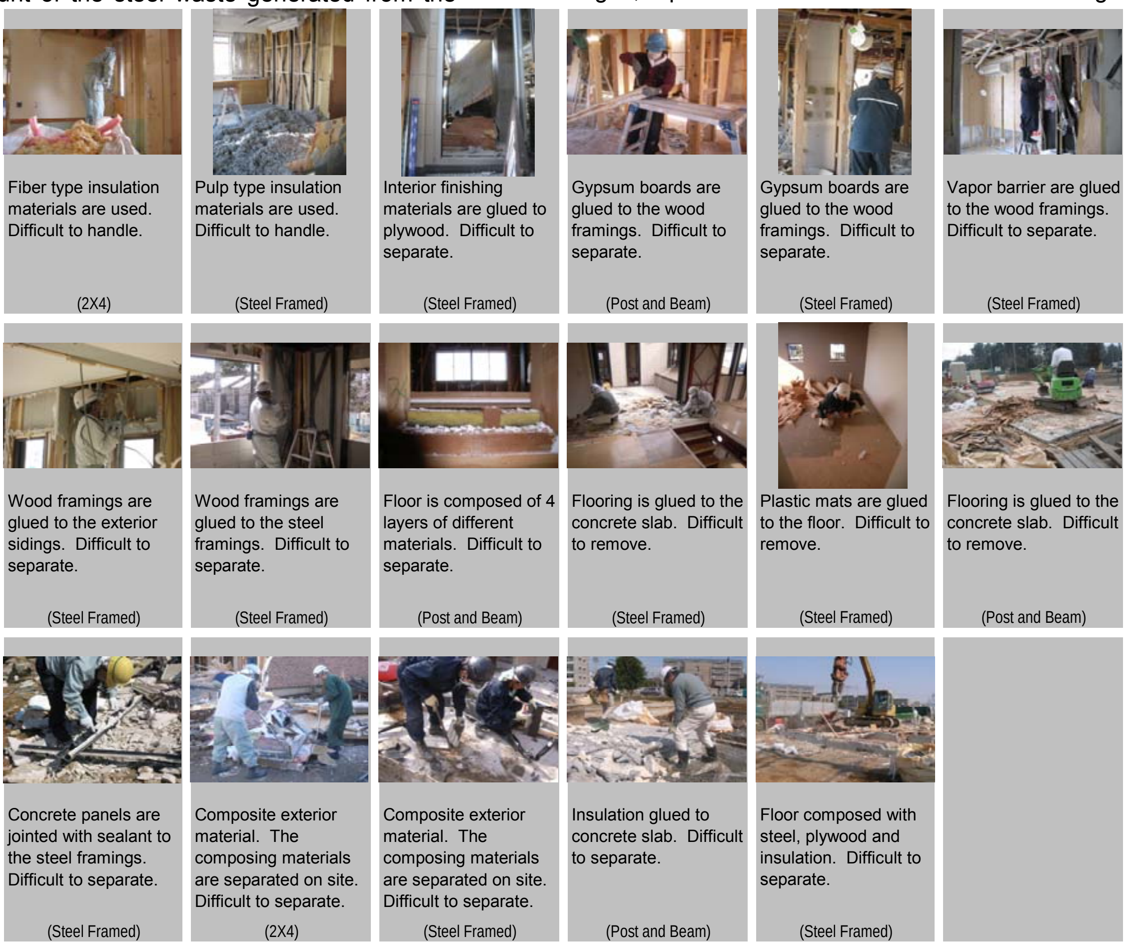
The amount of the wooden waste generated from wooden houses (House C, E and H) ranged from 0.05ton/m^2 to 0.13ton/m^2. Some of the wooden wastes are supposed to be treated as mixed waste. The total amount of the wooden waste and mixed waste is almost same for the 3 types of wooden house and it ranged from 0.13ton/m^2 to 0.14ton/m^2. The amount of the steel waste generated from the steel framed house (House M) was 0.25ton/m^2. The amount of the wooden waste generated from the steel framed house (House M) was 0.01ton/m^2. Most of the wooden waste generated from the House M are supposed be treated as mixed waste. The total amount of the wooden waste and mixed waste generated from the steel framed house M was 0.16ton/m^2.

Considering all these results the wooden waste generated from a unit area of single detached houses can be roughly defined as 0.15ton/m^2. As the average floor area of the Japanese houses is approximately 150m^2 it can be roughly said that one single detached house store 11tons of carbon.

The waste generated from the unit area of the two removed and rebuilt houses were less than those of the dismantled ones. The amount of the waste not including the concrete waste was 0.09ton/m^2 for House O and 0.06ton/m^2 for House P. The wooden waste generated from House O was 0.06 and it was less than half the wooden waste generated from the dismantled houses. This means that more than half of the wooden materials were reused and kept storing the carbon.

4.3 Undesirable design for deconstruction

Most of the workers were once troubled in removing and separating material from the dismantled or deconstructed houses. Figure 8 shows some example of the undesirable design for deconstruction. The followings are some of the bad designs, production and constructions being



Fiber type insulation materials are used. Difficult to handle. (2X4)

Pulp type insulation materials are used. Difficult to handle. (Steel Framed)

Interior finishing materials are glued to plywood. Difficult to separate. (Steel Framed)

Gypsum boards are glued to the wood framings. Difficult to separate. (Post and Beam)

Gypsum boards are glued to the wood framings. Difficult to separate. (Steel Framed)

Vapor barrier are glued to the wood framings. Difficult to separate. (Steel Framed)

Wood framings are glued to the exterior sidings. Difficult to separate. (Steel Framed)

Wood framings are glued to the steel framings. Difficult to separate. (Steel Framed)

Floor is composed of 4 layers of different materials. Difficult to separate. (Post and Beam)

Flooring is glued to the concrete slab. Difficult to remove. (Steel Framed)

Plastic mats are glued to the floor. Difficult to remove. (Steel Framed)

Flooring is glued to the concrete slab. Difficult to remove. (Post and Beam)

Concrete panels are jointed with sealant to the steel framings. Difficult to separate. (Steel Framed)

Composite exterior material. The composing materials are separated on site. Difficult to separate. (2X4)

Composite exterior material. The composing materials are separated on site. Difficult to separate. (Steel Framed)

Insulation glued to concrete slab. Difficult to separate. (Post and Beam)

Floor composed with steel, plywood and insulation. Difficult to separate. (Steel Framed)

Figure 8: Undesirable design for deconstruction.

observed.

(1) Use difficult to handle materials.

For example non-packaged fiber or pulp insulation materials. These materials can easily brew away all over the floor and become difficult to handle.

(2) Use materials composed with different types of materials.

(3) Glue finishing materials to the structural sub materials.

(4) Glue finishing materials or sub materials to the wood framings or steel framings.

(5) Glue different types of materials to compose slabs or walls.

(6) Seal the gap between the steel framings and the concrete panels.

5 CONCLUSION

The database for the dismantling process of the single detached houses was formed. The database gives useful information for the future designing of the buildings. Particularly the finishing materials are usually replaced say every 15 years during the service life of buildings. At least for these materials we should think about the alternative design that enables the resource circulation.

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A Neurofuzzy Knowledge Model for the Quantification of Structural Flexibility

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Abstract
An assessment tool in the form of a neurofuzzy knowledge model is proposed, intended to quantitatively express the performance of building structures in relation to the suitability of a building regarding its structural flexibility. Structural flexibility is seen as a critical design criterion in the development of buildings fostering a prolonged service life, whose performance is dependant on their level of adaptability. The knowledge model is designed as a hybrid neurofuzzy system, built upon the principles of Fuzzy Logic and neural networks.

Keywords:
adaptability, load bearing structures, structural flexibility, knowledge model, assessment tool

1 INTRODUCTION

Buildings nowadays tend to be more and more subject to the accelerating pace of modern society. The typical life span of a building in metropolitan Tokyo for instance is as short as seventeen years, and in numerous countries a serious shift in the focus of building activities can be noticed towards the refurbishment and replenishment of the existing and not seldom considerably young stock [1]. With this shortening in life cycles of buildings, an increase in discrepancies between functional, technical and economical service lives can be identified. These discrepancies contribute to the unwanted degeneration of the quality of the building stock, constraining the development of a sustainable built environment: the increasing influence of shortening functional service lives on life cycles as a whole and the typical linear metabolism of building activities put a heavy burden on the availability of natural resources, energy and space.

It is presumed that buildings intentionally designed to foster a prolonged service life, are able to address these issues [2]. However, instigated by among others the observed amplification of urban density, demographic diversity and shifts in the nature of work, future demands on a buildings' performance are becoming increasingly uncertain. Therefore, the embodiment of certain capacities to accommodate substantial change in the future is recognized as a key precondition for the successful and sustainable development of such buildings: capacities generally referred to as flexibility or adaptability**.**

In this paper the current development of an assessment tool is introduced to identify, and more importantly, quantify such capacities, in order to be able to actively implement features in favour of adaptability during the design phase of a building. The specific focus of this research concerns a buildings' main load bearing structure, as its qualities in relation to a certain level of adaptability are considered to be of critical importance.

The paper is structured as follows. In section 2 adaptability will be further evaluated, and more in particular the concept of structural flexibility. Section 3 will discuss the development of the assessment tool and its typical merits, and section 4 will elaborate on its implementation. Finally, in section 5 the preliminary conclusions of this research will be discussed.

2 ADAPTABILITY OF BUILDINGS

2.1 Feasibility of adaptability

Although the concept of flexibility or adaptability has surfaced in various appearances in the architectural debate for as long as nearly a century [3], little consensus is reached on how to pinpoint the matter, in particular in the case of issues related to service lives of buildings and consequently, sustainability. In general, adaptable buildings are considered to be able to provide a more efficient use of space, an increase in longevity and an overall improvement in operating performance. Nevertheless, within the context of the intended virtues of performance-based design, the need for clear and unambiguous criteria to establish a certain level of adaptability reverberates in several studies [4,5,6].

This need sterns from the notion that the definition of minimum functional requirements in order to assess the performance of a building, does not suffice to address the uncertainties concerned with changes in future demands on the serviceability of the building; defining minimum levels of adaptability could overcome these problems, provided their performance can be measured and used for comparison of alternative configurations.

The difficulties characterizing the subject, as pointed out by Durmisevic [7], originate from the notion that adaptability addresses spatial as well as technical information, complicated by the typical richness and often subjective nature of design information concerning a buildings' design process. This leads to a vast amount of complex direct and indirect relationships, hindering the optimization of a design as a whole.

2.2 Design strategies for adaptability

Adaptability as a design strategy is closely related to two other strategies attempting to enhance the long-term environmental performance of buildings, namely **Durability** and **Design for Disassembly**. For the purpose of this research solely focussing on adaptability however, three typical design strategies can be identified [1]:

- Design for Flexibility (DfF)
- Design for Convertibility (DfC)
- Design for Expandability (DfE)

Design for Flexibility

The strategy DfF is characterized by the pursuit of an open, systemized and exchangeable component configuration, minimizing functional integration of building parts and maximizing accessibility, thus increasing the range of options for future refurbishment without compromising overall performance.

Design for Convertibility

DfC as a design strategy is characterized by the employment of a fairly neutral spatial configuration and surplus in spatial performance, encompassing the possibilities for functional mutation or partitioning during the service life of a building.

Design for Expandability

The last strategy, DfE, is characterized by the creation of a surplus in technical performance, possibilities for partitioning and a minimization of structural transfer zones, all in favour of the ability to expand or extend a building plan.

Although identified as distinct strategies, they are nevertheless not mutually exclusive, and moreover currently lack clear guidelines on how to realize their intended outcomes. They do stipulate the circumstances under which certain levels of adaptability are feasible, and express some suppositions on characteristic configurations in favour of the aforementioned.

2.3 Structural Flexibility

As stated in the introduction, qualities regarding the main load bearing structure are of critical importance in relation to adaptability. Usually being the most static entity in a buildings' configuration in terms of its technical service life and use life cycle, a building structure represents an important share of a buildings' longevity potential as a whole, while concurrently expressing the largest possible hazard for friction when the pace of changing user demands is concerned. Furthermore, the considerable amount of resources, energy and subsequently environmental load involved during its life cycle, emphasizes the importance of a sustainable management of this asset.

Structural flexibility therefore, the ability to facilitate changes within the use of a building or its configuration without compromising structural performance, is considered to be a key precondition for the performance on adaptability as a whole. Note the passive disposition characterizing this approach, as opposed to a more active strategy, in which the main structure itself is exposed to substantial changes, denoted as structural adaptability in this context.

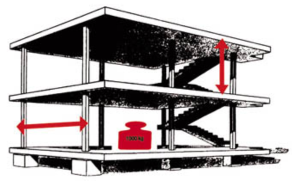

Figure 1: Bigger is better; obvious favourable capacities of load bearing structures concerning structural flexibility, particular in relation to spatial mutation.

In relation to the aforementioned design strategies, some favourable capacities of load bearing structures concerning structural flexibility can be identified. As Figure 1 denotes, large floor spans and ceiling heights contribute to the range of possibilities for multifunctionality or spatial mutation for instance, as well as a surplus in load bearing capacities of floor plans [8]. Optimizing these features however requires precise knowledge, and furthermore less evident characteristics might be of critical importance in a configuration as well.

3 ASSESSMENT OF STRUCTURAL FLEXIBILITY

3.1 Knowledge model

In order to actively implement features of structural flexibility therefore, all relevant attributes should be identified and their suitability measured and quantified. To achieve this, an assessment tool is currently being developed, intended to quantitatively express the performance of building structures in relation to the suitability of a building regarding its adaptability. This assessment tool is structured as a knowledge model, incorporating design knowledge through the systematic evaluation of fundamental interdependencies in the properties of a buildings' configuration. The choice for this formalism has some advantages. For instance, as it supports an object-oriented representation of knowledge, it can be extended on without compromising already implemented domain related expert knowledge.

Performance indicators assessing critical attribute relations are fed to the knowledge model as input variables, which, through a neurofuzzy computational paradigm, lead to a single score value output, expressing a normalized level of structural flexibility for the configuration under assessment. The characteristics and development of this model will be further discussed.

3.2 Taxonomy of interdependencies

With the desire to express the aforementioned interdependencies in a knowledge framework, the need arises to classify relevant design attributes involved in these relationships. To enable such a classification, a building configuration is represented through decisions made in three main design domains, namely the functional, technical and physical domain [7]. Based on models developed by Brand [9] and Leupen [10], an abstract building model is subsequently specified, serving as a taxonomy for the knowledge model. Its main taxons are derived from a buildings' typical functions, being structure, envelope, services, access and space plan. Aspects reaching beyond the scope of a building itself, such as those related to its location for instance, are omitted in this context.

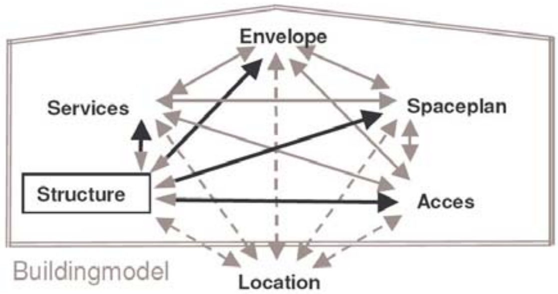

Figure 2: Abstract building model displaying the main taxonomy of interdependencies concerning structural flexibility, denoted with black arrows.

Within each main taxon, critical elements are identified, based on occurrence, positioning, mass, volume and service lives. The load bearing structure is subdivided into four taxons representing horizontal elements such as floor slabs and beams, vertical elements such as columns and load bearing walls, elements providing stability and the foundation. This taxonomy forms the basis for the identification of relevant functional, technical and physical interdependencies.

3.3 Key performance indicators

In relation to the aforementioned design strategies and the range of relations between elements of the main structure and critical elements in other building layers, key performance indicators were identified, serving as prototypes for the indicators to be implemented in the various nodes of the knowledge model displayed in Figure 4. The solution space for the assessment of structural flexibility is thus determined by two classes of criteria, defined as Autonomy and Suitability, each containing key indicators as depicted in Figure 3.

Autonomy

Adhering to technical aspects of adaptability, autonomy refers to qualities of the main structure concerning functional decomposition and independence in performance in relation to other functional entities, and can be subdivided into four key indicators:

- **Integration (INT)** - assessment of incorporation of independent functions in building components where load bearing elements are involved.
- **Redundancy (RED)** - assessment of independence in structural performance in relation to adaptations concerning the load bearing elements.
- **Penetration (PEN)** - ability to facilitate intersection of entities belonging to other functional abstractions.
- **Connection (CON)** - assessment of typology of interfaces between load bearing elements and other building components.

Suitability

Suitability on the other hand, refers to qualities expressing the serviceability of the structural configuration, adhering to spatial aspects of adaptability. As with Autonomy, this criterium can be broken down into four key indicators:

- **Spatial Surplus (SPA)** - surplus of space provided by the structural configuration.
- **Obstruction (OBS)** - assessment of morphological configurations, hindering the free positioning of entities, such as the distribution of technical services.
- **Technical Surplus (TEC)** - supply of load bearing capacity provided by the structural elements.
- **Accessibility (ACC)** - level of spatial access to building components adjacent to load bearing elements.

Assessment of performance

Within each of these indicators, several relevant attributes determining its performance are identified. For instance, the key performance indicator Connection is determined by an evaluation of the structural relevance of the joint in question, its topology, reversibility and technical life cycle. As already mentioned, each of these key indicators serves as a prototype for the assessment of a particular attribute relationship. The assessment of the typical bay width of a main structure in relation to the space plan for instance, is an implementation of the prototype Spatial Surplus.

In order to be able to aggregate the performance of each individual indicator, a mapping is applied between the evaluation of a certain aspect and a normalized level, ranging from zero to one, the latter representing an extreme high level of structural flexibility. The details on the computation involved will be discussed later on.

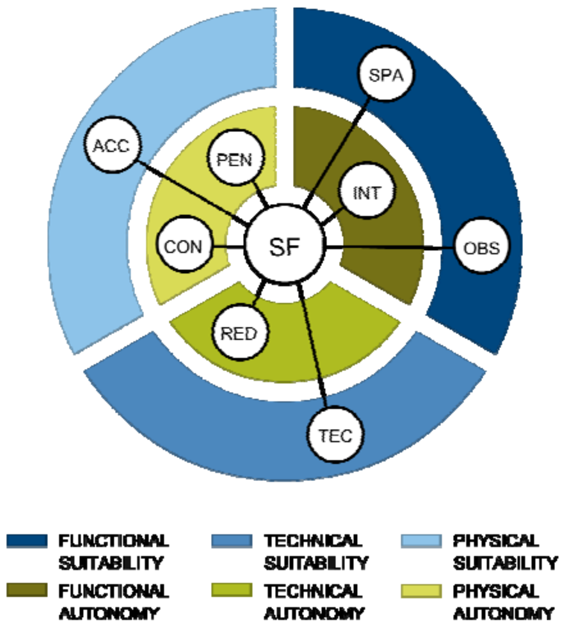

Figure 3: Key performance indicators determining structural flexibility, placed in their respective domains.

3.4 Topological structure

With a taxonomy of relevant building elements and prototypes for key performance indicators determined, the structure of the knowledge model can be discussed. The topology of this model, as displayed in Figure 4, is considered to be a feed-forward tree structure which is stacked in layers, ensuring causality among dependencies. A neural tree typically consists of terminal and non terminal nodes, connected to each other through links, passing through the output of one node to the next. These links also contain weighing factors, expressing the relative importance of inputs to a non terminal node. The various layers in the structure are denoted as the input layer, a set of hidden layers and finally the output layer. Each layer represents a different level of abstraction in the computation towards structural flexibility, ranging from low to high, starting at the input layer. The details of these layers are as follows:

input layer

The input layer contains the terminal nodes which are being fed with the independent variables, expressing the normalized score on the implemented performance indicators. Each terminal node represents a typical set of attribute relations, determined by the design domain in question, the functional abstraction or building layer, and a functional unit representing a structural element. As Figure 4 depicts, this accounts for 48 terminal nodes, as there are three design domains to be distinguished, four building layers related to and four main taxons of structural elements.

first hidden layer

In the first hidden layer containing non terminal nodes, for each of the structural taxons their scores in the functional, technical and physical domain is aggregated, related to a specific building layer.

second hidden layer

The four non terminal nodes in the second hidden layer represent the aggregated performance of the load bearing structure in relation to the functional abstractions envelope, services, access and space plan.

output layer

In the output layer performance of the underlaying functional abstractions is computed to a single score value. As with the connections between the nodes in earlier successive layers, weighing factors are used to express the mutual relative importance.

3.5 Computational paradigm

The nature of the problem statement requires the assessment tool on the one hand to be able to cope with complex, non linear and indirect attribute relationships, and on the other hand accomplish a translucent knowledge representation. These requirements limit the use of known computational paradigms [11], such as covariance analysis and independent component analysis for instance.

To accommodate these requirements, the use of a neurofuzzy system is proposed. Being a hybrid system built upon the principles of Fuzzy Logic and neural networks, it encompasses the merits of both techniques and effectively compensates their individual limitations. The use of a neural tree namely provides a framework for structuring information, while Fuzzy Logic enables a reasoning process capable of handling the imprecise form of decision making typical for ill-structured and ill-defined problems [12].

Fuzzy Logic

Based on the fuzzy set theory [13], Fuzzy Logic offers a computational paradigm able to deal with lexical uncertainty. In this context Fuzzy Logic is applied in the various nodes of the knowledge model. The normalized performance indicators serving as input variables are translated into fuzzy variables, expressing the uncertainty accompanied by their evaluation. Calculation is then carried out throughout the model using inference rules, enabling the modelling of highly non linear relationships.

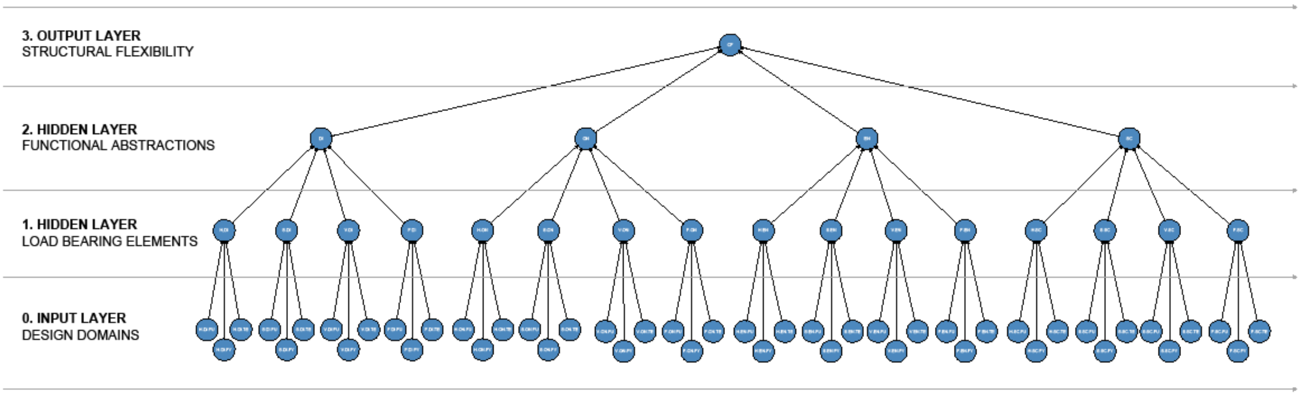

Figure 4: Topology of the knowledge model.

Neural networks

Favourable aspects of neural networks are applied in the knowledge model where inference is concerned. With the use of Fuzzy Associative Memories, basically being fuzzy logic rules with an associated weight, nodes with blocks containing inference rules can be subjected to training by supplying them with data sets consisting of an input/output mapping. In this way, specific nodes can be trained for a specific set of relationships, without affecting earlier established weighing factors or the overall structure of the model.

3.6 Validation

As the assessment tool is still in development, its reliability is yet uncertain. Nevertheless, several techniques are available to verify its projected outcome. For instance, the aforementioned data sets to be used for training nodes in the model could be obtained by the use of an expert panel, evaluating various scenarios supplied. These evaluations can be correlated, thus establishing a certain notion of its reliability. Furthermore, the weighing factors linking the various nodes can be obtained likewise, validating their consistency through the use of the Analytical Hierarchy Process (AHP) [14].

4 EXPECTED IMPLEMENTATION

The knowledge model is expected to serve its purpose in the assessment of existing load bearing structures on their potential for a certain level of structural flexibility, as well as a design tool in the development of new buildings fostering a prolonged service life through the implementation of adaptability as a design strategy. More importantly, its merits can provide the means to optimize specific design problems concerning structural flexibility and adaptability in general, as interdependencies in design decisions are being made more translucent.

5 DISCUSSION AND CONCLUSIONS

The assessment tool currently in development provides a robust framework in the pursuit of the quantification of structural flexibility as a design criterion in the design process of buildings with an intended longevity. Furthermore, through the systematic evaluation of relevant attribute relationships, insights on the characteristics of adaptability, and in particular structural flexibility, are considered to be heightened.

On a different note, one could say that the approach discussed in this paper could serve other building disciplines as well in the pursuit of acquiring knowledge within their domain in the context of adaptability. For instance, from a point of view concerning technical services, the quantification of critical attribute relations with entities from other functional building layers could possibly establish guidelines for optimizing the design of typologies for distribution nets, or installation systems as a whole.

Ideally, the integration of knowledge obtained from different disciplines with respect to adaptability could truly lead to the adoption of successful design strategies with a sustainable and viable building stock as their biggest merit.

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Construction Materials and C&D Waste in India

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Abstract
Construction and demolition (C&D) waste generation and handling issues have been in focus to achieve sustainable goals. Owing to growth in construction in India, it is appropriate to link generation of C&D waste with the growth. If measures to minimize and handle the C&D waste are not developed and efficiently adopted it may threat the environment as well as sustainable movement of Indian construction industry. C&D waste in India in 2010 may be estimated as 24 million tonnes. This paper provides an overview of the construction industry in India and gives some statistics about the volume of C&D waste.

Keywords:
Construction and Demolition Waste, Recycling, Sustainable Construction, Demolition

1 INTRODUCTION

U.S. Environmental Protection Agency (EPA) defines construction and demolition (C&D) waste as waste materials consist of the debris generated during the construction, renovation, and demolition of buildings, roads, and bridges. C&D materials often contain materials that include: concrete, asphalt, wood, metals, gypsum, plastics and salvaged building components. It is a challenging task to handle C&D waste because it is bulky, heavy and inert and also mixture of various materials of different characteristics. It is also difficult to choose any suitable disposal method, for example, it cannot be incinerated due to its high density and inertness. With the advent of sustainable practices in the construction industry, C&D waste generation and handling issues have been in focus to achieve the sustainable goals for our common future. Reduce, Reuse, Recycle (3Rs) philosophy is highly useful in handling of C&D waste. Though recycling had already been taken place at the time of Second World War when Germany reused most of the demolished concrete for construction purposes, yet many countries, especially developing countries are not fully aware of potential of 3Rs and hence still find land filling as the only method for C&D waste handling. The better practice to handle C&D waste is to minimize generation of C&D waste, but sometimes it is unavoidable due to various issues such as change-orders or demolition requirements for redevelopment.

Globally, building waste production of 2 to 3 billion tonnes per year is estimated, of which 30-40 % is concrete [1]. C&D waste issues are more important for the developing countries, which are entering or already entered in construction boom era. According to the annual report of Dubai municipality's Waste Management Department, a total of 27.7 million tonnes of construction waste were removed from various construction sites in the city in 2007, recording growth of 163 % in comparison to the waste generated in 2006, just 10.5 million tonnes [2]. In their study, Vilas and Guilberto [1] found that many countries in Asia do not have specific regulations designed for C&D wastes, although some countries include some sections in their solid waste management regulations and/or related policies. According to the study, developed countries generate 500 to 1000 kg per capita per year building & construction waste and waste in European Countries is estimated to be 175 million tonnes/year. It was also mentioned that very small percentage of waste from construction industry is reused or recycled, the majority being deposited or used as landfill.

Like other developing countries, India is also enjoying construction boom. With the rapid growth in construction activities of India it is appropriate to link the generation of C&D waste with the growth of construction industry and related issues. It is also essential to study C&D waste generation and handling to develop accurate data and establish sustainable methods to manage construction waste.

2 INDIAN CONSTRUCTION INDUSTRY

According to 11th five year plan [3], in terms of magnitude construction industry is second only to agriculture. Based on an analysis of the forward and backward linkages of construction, the multiplier effect for construction on the economy is estimated to be significant. With around 27,770 enterprises involved directly in the activity of construction in 2005, the industry is one of the largest employers in the country and is characterized by a mix of both organized and unorganized entities. The employment figures have shown a steady rise from 14.6 million in 1995 to more than double in 2005 that is 31.46 million personnel comprising engineers, technicians, foremen, clerical staff, and skilled and unskilled workers. With several ambitious projects anticipated during the 11th Plan, the demand for construction manpower is going to grow at a consistent pace of at least 8%–9%, thereby resulting in an annual accretion of around 2.5 million persons to the existing stock [3].

The construction industry sets in motion the process of economical growth in the country. Over US$ 100 billion has been invested in this sector during 2004-2005, with the private sector contributing to 32.7 per cent of this investment. This sector is likely to continue to record higher growth in the coming years due to the Government of India's (GOI) recent initiative to allow 100 per cent foreign direct investment in real estate development projects [4]. As shown in Figure 1, construction share in total GDP has grown from 6.4% in 2000-01 to 7.2% in 2004-05 [5]. Technology Information, Forecasting and Assessment Council (TIFAC) study mentions that total construction work for five years during 2006-2011 is equivalent to $847 billion [5].

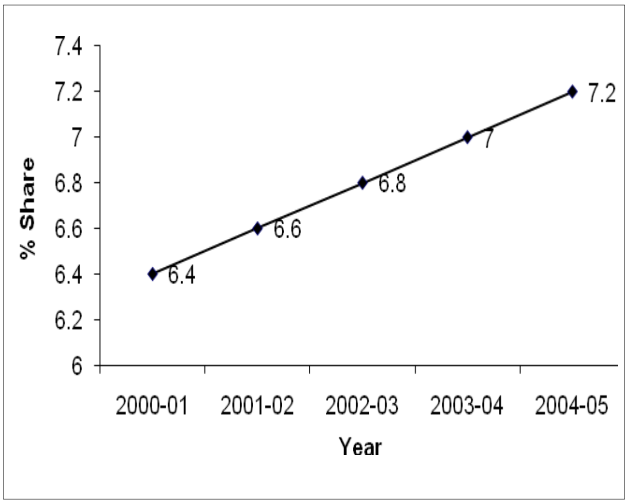

Figure 1: Percentage share of construction in total GDP.

Table 1 shows investment (in US billion Dollars) in the construction industry from 1998 to 2002, presented by Laskar and Murty [6].

Year	1998	1999	2000	2001	2002
Residential Construction					
	2.14	2.26	3.57	4.16	4.28
Non Residential Construction					
	3.80	3.92	3.57	4.04	4.40
Civil Eng. Construction					
	44	47.86	55.47	63.21	72.2
Total					
	49.94	54.04	62.61	71.41	80.9

Table 1: Investment in the construction industry, amount in USD billion.

Based on the above data, values for year 2008 to 2011 were estimated assuming the same rate of growth. Table 2 presents the estimated values, which were read from the graph shown in Figure 2.

Year	2008	2009	2010	2011
Residential Construction				
	8.00	8.62	9.24	9.86
Non Residential Construction				
	5.19	5.33	5.45	5.58
Civil Eng. Construction				
	115.24	122.38	129.52	136.55
Total				
	128.43	136.33	144.21	151.99

Table 2: Estimated investment in Indian construction industry, amount *in USD* billion.

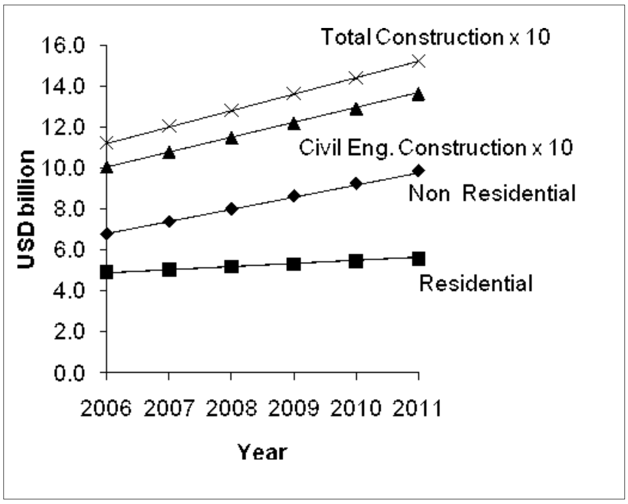

Figure 2: Estimated investment in Indian construction industry.

Table 3 shows the distribution of cost among various modes of expense in Indian construction industry [7].The importance of materials cost in construction industry can be seen from the fact that the component of materials cost comprises nearly 40%–60% of the project cost. This percentage is higher for projects such as building, railway, and transmission, and lower but still a critical part of other projects such as power and mineral plant. In addition, the Indian construction industry is the largest consumer of material resources of both natural such as stone, clay, lime and the processed and synthetic resources [4].

According to "India – A building Industry in Transition" [8] many positive and negative points are associated with Indian construction industry. Continuing strong economic growth, foreign investment, cheap & plentiful labor, strong engineering education systems are some of the positive points. On the other hand, inflationary pressures, relatively low skilled and uneducated labors, government bureaucracy, and lack of infrastructure are some of the negative points that make the construction activity more challenging. It also suggests that there is an urgent requirement for a government sponsored 40–50 year holistic infrastructure plan for India to continue on its high growth path towards economic maturity.

	Materials %	Construction equipment %	Labor %	Finance %	Enabling Expenses %	Admin. Expenses %	Surplus %
Building	58-60	4-5	11-13	7-8	5.5-6.5	3.5-4.5	5-6
Roads	42-45	21-23	10-12	7-8	5.5-6.5	3.5-4.5	5-6
Bridges	46-48	16-18	11-13	7-8	5.5-6.5	3.5-4.5	5-6
Dams, etc	42-46	21-23	10-12	7-8	5.5-6.5	3.5-4.5	5-6
Power	41-43	21-24	10-12	7-8	5.5-6.5	3.5-4.5	5-6
Railway	51-53	6-8	16-18	7-8	5.5-6.5	3.5-4.5	5-6
Mineral plant	41-44	20-22	12-14	7-8	5.5-6.5	3.5-4.5	5-6
Transmission	49-51	5-7	19-21	7-8	5.5-6.5	3.5-4.5	5-6

Table 3: Percentage cost distribution in construction industry.

According to Eleventh Five Year Plan [3], the major challenge that the construction industry faces is to raise its delivery capabilities commensurate with the targets for sectors such as transportation, housing, and urban development. The planned development of infrastructure would face constraints, unless the construction industry improves the delivery potentials by addressing crucial issues and impediments by bringing in systemic changes. The major issues in the construction industry include productivity, construction cost, contract procedures, dispute resolution, safety issues, construction finance, and environmental issues. This plan also suggests that, aspects related to enhanced quality in construction products should be accorded attention at all levels. To achieve this, the Performance Appraisal Certificate Scheme is being implemented for the development and promotion of materials, products, and systems under the joint initiatives of Building Materials and Technology Promotion Council (BMTPC), Construction Industry Development Council (CIDC), Bureau of Indian Standards (BIS) and other agencies. BIS and Indian Bureau of Mines are the main authorities for issuing and maintaining the codes/standards pertaining to safety and other practices in the Indian construction industry.

GOI permits foreign investment up to 100 per cent for development of integrated townships, including housing, commercial premises, hotels, resorts, city and regional level urban infrastructure facilities such as roads and bridges, mass rapid transit systems and manufacture of building materials. The GOI permits imports of building materials and products under open general license system. Under the Government of India's new Export-Import Policy, the duty on building products is pegged at 15 percent. The GOI has announced its intention to reduce progressively the import duty rates [4].

Eleventh Five Year Plan suggests that following measures should be adopted by the construction industry to achieve the desired growth in construction sector and to align it with global trends in terms of growth, quality, and competitiveness [3]:

- Improve productivity through introduction of efficient technologies and modern management techniques.
- Reduce transactional costs by reviewing contract procedures and dispute resolution mechanisms.
- Enhance quality standards and provision of adequate institutional finance to the construction sector.
- Develop a National Plan for human resource development through training and certification of construction personnel.
- Accord greater importance to safety in construction activities by establishing trained and certified Safety Management Teams.

3 ENVIRONMENTAL REGULATIONS RELATED TO INDIAN CONSTRUCTION INDUSTRY

According to Eleventh Five Year Plan[3], sustainable development concepts applied to the design, construction, and operation of construction projects can enhance both the economic well being and the environmental health of communities. Ministry of Environment and Forest (MOEF) recognizes Environmental Impact Assessment an important tool for integrating these objectives and it should be a necessary pre-condition before construction projects beyond stipulated size are approved. Further, initiatives for ensuring adherence to international standards and regulations, such as the Environment Protection Act 2006 and the Energy Conservation Act 2001 are also required. Various interdisciplinary organizations such as CIDC and BMTPC have been set up to address the issues of environment-friendly technologies and energy efficiency in building materials. Central and State Pollution Control Board (CPCB) approves, monitors, and regulates projects from all sectors including construction, keeping in view their impact on environment. According to Municipal Solid Wastes (Management and Handling) Rules of 2000, C&D wastes or debris shall be separately collected and disposed of [9].

4 CONSTRUCTION & DEMOLITION WASTE IN INDIA

4.1 Components

In India C&D waste has two components [5]:

<u>Major components</u>

- Cement concrete
- Bricks
- Cement plaster
- Steel (from RCC, door/window frames, roofing support, railings of staircase etc.)
- Rubble
- Stone (marble, granite, sand stone)

- Timber/wood (especially demolition of old buildings)

<u>Minor components</u>

- Conduits (iron, plastic)
- Pipes (GI, iron, plastic)
- Electrical fixtures (copper/ aluminum wiring, wooden baton, switches, wire insulation)
- Panels (wooden, laminated)
- Others (glazed tiles, glass panes)

Figure 3 and Table 4 show the percentage distribution and tonnage of various constituents of C&D waste in India in 2000, respectively [5].

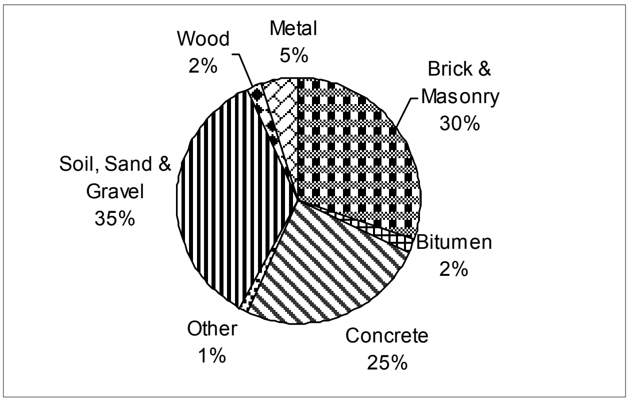

Figure 3: Different constituents of C&D waste.

Constituent	million tonnes/yr
Soil, Sand and gravel	4.20 to 5.14
Bricks and masonry	3.60 to 4.40
Concrete	2.40 to 3.67
Metals	0.60 to 0.73
Bitumen	0.25 to 0.30
Wood	0.25 to 0.30
Others	0.10 to 0.15

Table 4: Quantity of various constituents generated per year.

4.2 C&D waste handling

In India, contractors play an important role in waste management. Contractual arrangements require that demolition wastes have to be disposed off by the contractor at his cost. Other than new construction, renovation or repair of buildings, demolition of an existing building/structure is the main cause of waste generation from the construction industry. In India, services of demolition contractors are taken when an old building is to be demolished due to deterioration of the building or to make way for construction of a new building [5]. According to TIFAC study,

- Items recovered during demolition are sold in the market at a discount with respect to price of new material.
- Items, that cannot be re-used, are disposed to landfill site.
- Some municipal corporations allow C&D waste in their landfills, while others want to minimize it to prolong useful life of landfill sites.
- Different constituents of waste are not segregated prior to disposal.
- Builders/ owners bear the cost of transportation, which at present, ranges between US$ 6 to 13 per truckload depending on the distance of demolition site from landfill area.
- Municipal authorities incur cost of US$ 1.50 to 2 per tonnes of waste, but presently no charge is levied by them on the owner or builder
- Though directives exist for disposal of waste to landfill areas, presently penal action against violators is practically not taken.

4.3 C&D waste estimation

Various studies have been done to estimate the quantity of C&D waste in India. Pappu, Saxena et al [10] presented 14.5 million tonnes/year C&D waste in India. CPCB estimated quantum of solid waste generation in India to be to the tune of 48 million tonnes per annum for year 2000, out of which waste from construction industry accounted for about 12 to 14.7 million tonnes [5]. As shown in Figure 4, Singhal and Pandey [11] presented the growth in municipal solid waste in India. This graph can be used for rough estimation of C&D waste based on assumption that C&D waste is estimated to be 25-30% of municipal solid waste [5].

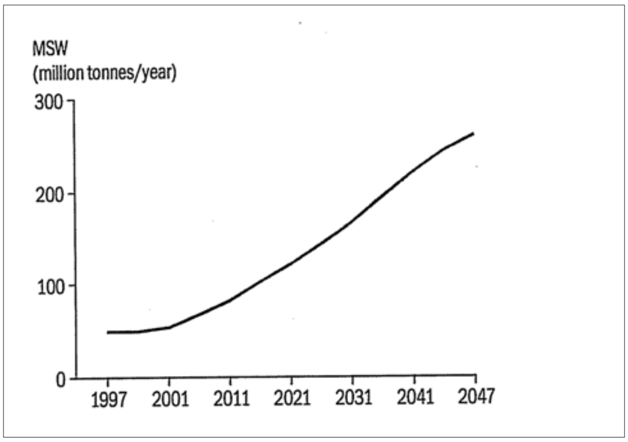

Figure 4: Municipal solid waste generation in India.

Therefore, from Figure 4 total C&D waste generated in year 2000 was approximately 13-15 million tonnes. Comprehensive study for C&D waste estimation was done by TIFAC [5]. This study presented following data related to C&D waste in India for the year 2000:

- C&D waste was estimated as 14.69 million tonnes.
- Waste generation during construction and renovation/ repair work was 40 to 60 and 40 to 50 kg/m^2 respectively.
- The highest contribution to waste generation was from demolition of buildings, which yielded on average 425 kg/m^2 of waste.

Table 5 represents the comparative study of C&D waste for India & USA for the year 2000. The data for USA were collected from CIB TG 39 reports [12].

	Description	India	USA
1.	Year	2000	2000
2.	C&D waste generation a) New Construction b) Renovation /Repair c) Demolition	 50 kg/m^2 45 kg/m^2 425 kg/m^2	 41 kg/m^2 118 kg/m^2 515 kg/m^2

Table 5**:** C&D waste data for India and USA.

Figure 4, C&D-municipal solid waste ratio assumption, and TIFAC study could be used to estimate C&D waste for future years. For example, C&D waste in India for the year 2010 may be estimated as 22-26 million tonnes by using Figure 4. This range is in agreement with the 24 million tonnes C&D waste value for the year 2010, which is estimated by following the procedure used in TIFAC study [5].

5 SUMMARY

Owing to growth in construction, it is expected that C&D waste generation in India will increase. If measures to minimize and handle the C&D waste are not developed and efficiently adopted, it may threat environment as well as sustainable movement of the country. C&D waste minimization and handling are necessary in view of limited landfill space and increasing quantum of demolition waste otherwise there may be issues related to handling the waste and finding space for landfilling. This will cause an extra burden on solid waste management plans, which are already looking for new ways to fight with the growth in municipal solid waste due to increase in urban population and developments in the country. Government policies and laws should be reformed to motivate and make C&D waste management mandatory for all types of construction activities. It would be desirable to have more accurate and detailed data such as C&D waste generation and the way it is managed in India. 3Rs policy and use of waste minimizing technologies e.g. design for deconstruction and reuse of materials should be adopted to minimize C&D waste. Recycling of C&D waste by converting it to aggregate may offer dual benefit of saving landfill space and reduction in extraction of natural raw material for new construction activities, leading towards sustainable development.

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Embodied and operational energy use of buildings

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Abstract

Up to now energy savings in buildings have been approached from the side of their operational energy. However, when the operational energy use is reduced, the embodied energy use (i.e. the energy embodied in the manufacture and transport of building components) could become an important item. In this paper we present the results of an energy flow investigation, based on LCA considerations, on the relative values of embodied en operational energy of dwellings and dwelling renovation. The environmental effects resulting from energy use are addressed as well.

Keywords:

Life cycle assessment, embodied energy, materials, operational energy use, passive houses

1 INTRODUCTION

Energy savings in the built environment have a high priority on the politic and scientific agenda. Costs savings, security of supply and the environment are the main reasons to save energy. When the operational use for heating is reduced considerably, the energy embodied in the manufacture and transport of building components (embodied energy) could become an important item. In the past, there have been few studies of the embodied energy of conventional dwellings. The energy use of an Australian house has been analysed for a thirty-year life cycle in [1], where the relative importance of energy consumption with respect to the way the house is used and to household behaviour was stressed. The relative values of the embodied and operational energies were found to be an important factor in choosing design strategies, such as insulation ([2], [3]). In [4], the embodied energy in a refurbishment project is compared with the embodied energy for demolition and new construction. It was found that the demolition of buildings should be regarded as environmentally unfriendly. These papers provided an analysis that focused on energy use, but did not consider other environmental effects. Environmental effects were considered in [5], to compare three types of dwellings. The results were aggregated for the entire life cycle of the building. Some of the impacts that were used in [5] to determine the final environmental profile of the dwellings were interdependent (e.q. energy and global warming potential), possibly resulting in a distorted profile.

The present paper is based on the method developed in [6] and presents first the results of a research on the relative value of operational and embodied energy use for renovation measures and for energy efficient new built dwellings. Second, the paper elaborates on the fact that energy use in itself is not an environmental problem, but the cause of a number of environmental problems. The relationship between energy use and environmental impact is studied using a LCA (Life Cycle Assessment) approach.

2 EMBODIED AND OPERATIONAL ENERGY USE IN RENOVATION

The production of the building components that are needed when building or renovating a dwelling costs energy. This energy is needed to extract the raw materials, to transport them and to produce the components. The overall energy use of building activities can be quantified by using Life Cycle Assessment (LCA). EcoQuantum, version 2.00 ([7], [8]) was used. EcoQuantum is a Dutch LCA tool for assessing the environmental effects of buildings in terms of material use, energy consumption, water consumption and environmental impacts. EcoQuantum uses a particular Dutch database of building materials maintained by IVAM. The impact assessment method is based on the CML-2 method. The role of the EcoQuantum tool with respect to other international LCA tools was discussed in [9] and [10].

During a life cycle assessment the energy use, the type of energy and the environmental effects are mapped from cradle (raw materials extraction) to grave (disposal), according to [11]. This includes production process and operational energy and material use. The operational energy use is defined as the energy needed to heat, cool and ventilate the dwelling and to power electrical appliances in the dwelling. In the present study, the operational energy use is limited to the energy use for heating and ventilating. Opposite to the operational energy use that can be calculated simply by using the U-values of the construction parts, the embodied primary energy use can only be calculated if the types and masses of materials used are known. The calculations in the present study were conducted for a terraced house, representative of houses build between 1966 and 1976 in the Netherlands ([12], [13]). The operational energy use of the dwelling was calculated using the EPA software [14]. The main characteristics of the dwelling before renovation are given in Table 1. To calculate the primary energy use related to electricity, the average efficiency of a Dutch electricity plant was used (0.39). The non-renovated dwelling is heated by a standard efficiency combination boiler. Auxiliary energy for pumps, ventilators and other HVAC equipment is taken into account, as well as the

Useful floor area (m^2)		139	
Ground floor	Surface area (m^2)	56	
	U-value (W/m^2K)	2.3	
Roof	Surface area (m^2)	66	
	U-value (W/m^2K)	1.0	
Facades (excl. windows)	Surface area (m^2)	36.2	
	U-value (W/m^2K)	1.8	
Windows	Surface area (m^2)	17	16
	U-value (W/m^2K)	5.1	2.9
Space heating & hot tap water		Standard efficiency combination boiler	
Ventilation		Natural	
m^3 gas/year for space heating		1242 (=39371 MJ primary energie)	
m^3 gas/year for hot tap water		506 (=16040 MJ primary energy)	
kWh/year auxiliary energy		427 (= 3942 MJ primary energy)	
MJ Total primary energy / year		59354	

Table 1: Main characteristics of the reference dwelling

electrical energy needed to power the heat pump (in variant 4). The electricity use related to lighting and white and brown goods is not taken into account. Six renovation variants are studied.

Variant 1

In variant 1 the façades (including roofs and ground floor, but excluding windows) are insulated. The U-value of the façade is then 0.35 W/m^2K, the U-value of the roof 0.31 W/m^2K and the U-value of the ground floor is 0.34 W/m^2K. For the facades and the roof stone wool insulation is used and finished by a coat of plaster. The ground floor is insulated with a Tonzon thermocushion (foldable insulation) with a Rc-value of 2.25 m^2K/W.

Variant 2

In variant 2 the single and double glass windows are replaced by high efficiency glass with an equivalent U-value of 1.7 W/m^2K.

Variant 3

The standard efficiency combination boiler is replaced by a steel high efficiency boiler with pomp control. In the calculation for the embodied energy all parts of the boiler were taken into account, which includes thermostat, vessels, control blocks, ventilator and façade duct set.

Variant 4

The standard efficiency combination boiler is replaced by a stainless steel high efficiency boiler combined with a heat pump boiler for hot tap water. The heat source of the heat pump boiler is indoor air.

Variant 5

The standard efficiency combination boiler is replaced by a steel high efficiency boiler and by 2.7m2 solar collector and a stainless steel solar boiler vessel for hot tap water.

In addition the heat distribution system (steel pipes and radiators) is completely replaced in variants 3, 4 and 5.

Variant 6

A balanced ventilation system is used, with a direct-current ventilator. The balanced ventilation unit consists of a galvanized steel heat exchanger, two ventilators, control blocks and steel ducts and grilles. The air tightness of the dwelling is reduced as well.

For the service life of the components, the standard life span as given in [15] was used: 75 year for insulation material; 35 year for distribution pipes; 30 years for radiators and heat pumps; 25 year for glazing and solar boilers; 15 years for boilers and mechanical ventilation and 8 years for pumps. When the life span of the building is longer than the life span of a component, the component is replaced at the end of its service life by a new, but identical component. The calculations account solely for the embodied energy use of the renovation measures described here above (therefore the energy embodied in the parts of the house that are not renovated is not accounted for).

The principle of the calculations is shown in figure 1, per m^2 surface area of the dwelling: in year 0, the year of renovation, energy is used to produce and place the new building components (embodied energy). Therefore there is more initial energy use when the building is being renovated than when it is not. The operational energy use decreases after renovation. Figure 1 shows the cumulated values of the energy use all over the years. The slope of the lines includes the replacement of the components at the end of their service life (linearized value). It shows that the energy embodied in a combination boiler (123 MJ/m^2 surface area) or in a combination and heat pump boiler (156 MJ/m^2 surface area), or in a solar boiler (218 MJ/m^2 surface area) is clearly higher than the energy embodied in insulation materials (26 MJ/m^2 surface area). However, the embodied energy use is paid back by the lower operational energy use in less than 5 years – in all cases. The shortest energy pay-back time is achieved by insulation measures (variants 1 and 2) and the longest by the heat pump boiler (variant 4).

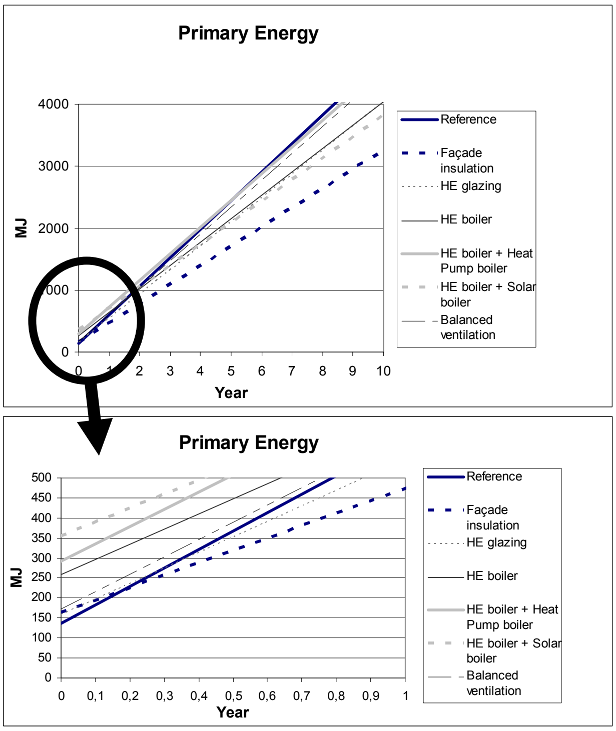


Figure 1: Cumulated embodied and operational energy use per square meter useful floor area over 10 years (upper graphic) and zoomed over 1 year (lower graphic).

Figure 2 shows the operational and embodied energy use for the reference dwelling and the different renovation variants after 30 years. The energy saving varies between 31% (façade insulation) and 6% (balanced ventilation and heat pump boiler). Gas is the primary energy for space for hot tap water, except for variant 4, for which it is electricity. Therefore the primary energy use for hot tap water was added to the electrical auxiliary energy in variant 4 (heat pump boiler). The auxiliary energy is higher in variant 6 than in the other variants (with the exception of variant 4), because of the use of ventilators for the ventilation. After 30 years of use, the embodied energy represents a small percentage of the total energy use, less than 6%. By considering only the operational energy use, the total energy savings are overestimated, but this has hardly an effect on the relative values for the different variants. The results are not expected to be very different for passive house renovation, where large quantity of insulation materials are used, but a more detailed study should be conducted.

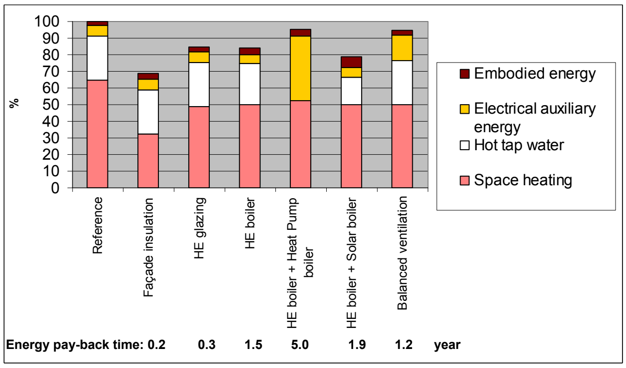


Figure 2: Embodied and operational energy use after 30 years for the different variants.

3 EMBODIED AND OPERATIONAL ENERGY IN LOW ENERGY NEW-BUILT

For this part of the research, the Ecobuild dwellings were used. These dwellings are very low-energy test dwellings used by ECN [16]. Dwellings A, B and C were compared with a reference dwelling. Dwellings A, B and C are very well insulated and all have a comparable insulation level, but the materials and HVAC equipment used are different. The main characteristics of the buildings are shown in Table 2. The service life of the building was set at 75 years. The life spans of all components can be found in [16].

It appears from figure 3 that the cumulated operational energy use during the whole service life can be halved if building concepts B and C are used instead of A or the reference. However, the energy embodied in dwellings B and C is higher than in the reference dwelling. Dwelling C performs better than the reference dwelling after only 6 years. Dwelling B needs 15 years to perform better and dwelling A 25 years. The energy embodied in the reference dwelling represents about 15 years of operational energy. Comparable values were found for instance in [1]. The energy embodied in low-energy dwellings A, B and C represents 34, 61 and 43 years of their operational energy respectively. This clearly means that the further reduction of the environmental impacts of dwellings will necessitate the reduction of their embodied energy use, because the embodied energy use may be responsible for more than half the total energy use for heating and ventilating.

	Refe-rence	Dwelling A	Dwelling B	Dwelling C
Insulation(Rc in m^2K/W)	3, double glass	>5, 3 layer glass	>5, 3 layer glass	>5 3 layer glass
Construction	bricks	Con-crete	Con-crete	timber
Inner walls	Partly bearing	Non-bearing	Non-bearing	Non-bearing
Ventilation	Nat/Mech.	Nat/Mech.	Balanced	Balanced
Space Heating	HE-Boiler	HE-Boiler	Heat pump	Heat pump
Primary energy use for heating (MJ/year)	43781	30194	17801	19456

Table 2: Main characteristics of the dwellings.

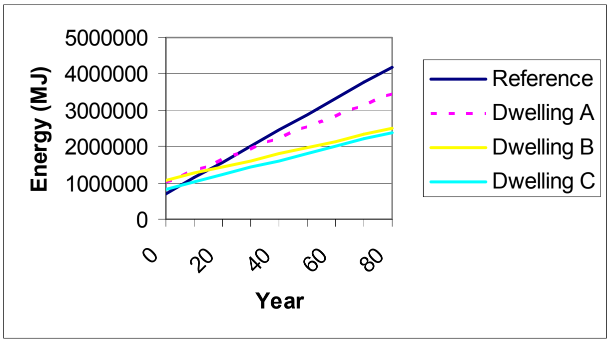


Figure 3: Embodied and operational primary energy use of the Ecobuild dwellings.

4 FROM ENERGY USE TO ENVIRONMENTAL EFFECTS

Environmental effects are measurable damages to the environment. The use of fossil fuels to produce energy is not an environmental effect, but a cause of a number of environmental damages. In LCA studies with EcoQuantum, nine environmental effects are addressed: abiotic depletion; global warming; ozone layer depletion; photochemical oxidation; acidification; eutrophication; humane toxicity; fresh water aquatic ecotoxicity and terrestrial ecotoxicity. In this section the concept of environmental pay-back time is used, similarly to the energy pay-back time defined in the previous section. It describes after how many years the environmental effect arising from renovation or building activities, pays itself back by a lower environmental effect because of a lower operational energy use for heating. In our opinion, the notion of environmental pay-back time, which is not used in conventional LCA (i.e. as described in [10]), is needed because unlike conventional consumer goods, buildings often change in the course of their life span. Components are replaced or removed, according to their technical and functional life cycles ([17]). Life Cycle Assessment is a static method that sums up all environmental effects during the life cycle of the product ([18]). However, the behaviour of buildings is dynamic. Therefore, it is difficult to track the environmental effects of changes in buildings using a life cycle assessment ([19]). As the development of a dynamic LCA method is far beyond the scope of this project, it was decided to adapt calculations to the dynamic aspects of a building by making a series of LCA calculations for different life spans of a building, from 0 to 80 years. This way we are able to study the effect of the service life and to calculate environmental pay-back times.

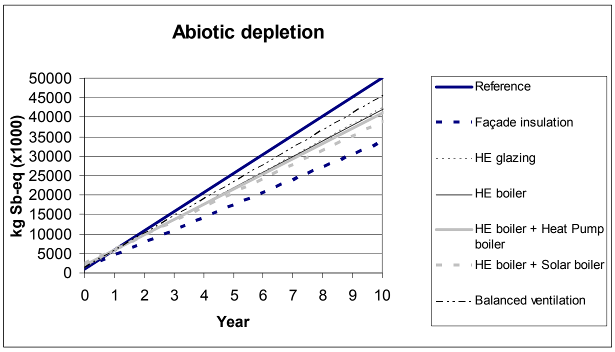
4.1 Renovation

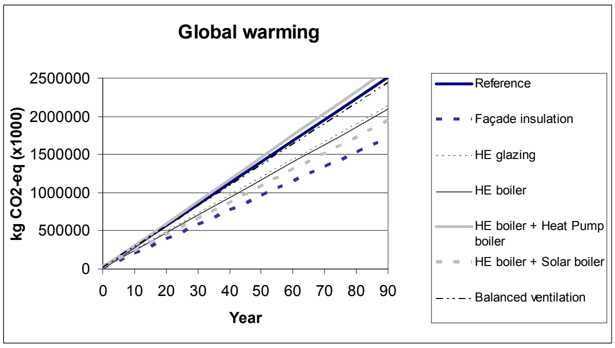
Figure 4 show examples of the cumulated values of the environmental effects abiotic depletion, global warming, ozone layer depletion and terrestrial ecotoxicity for the different renovation variants studied in chapter 2. The embodied environmental effect can be seen in year 0. The slope of the line represents the linearized environmental effect from operational energy and material use (replacements). Comparison of figure 4 with figure 1 (primary energy use) shows that the primary energy gives a good indication of abiotic depletion and to a lesser extend of global warming. It doe not reflect correctly the trends of the other environmental effects. For abiotic depletion – as for the primary energy use, all variants perform better than the reference after very few years. This is also the case for global warming, with the exception of variant 4 (heat pump boiler) that performs always worse than the reference. For terrestrial ecotoxicity all variants relating to heating and ventilating equipment perform worse than the reference. The variants with insulation perform better than the reference. For ozone layer depletion, the results are miscellaneous.

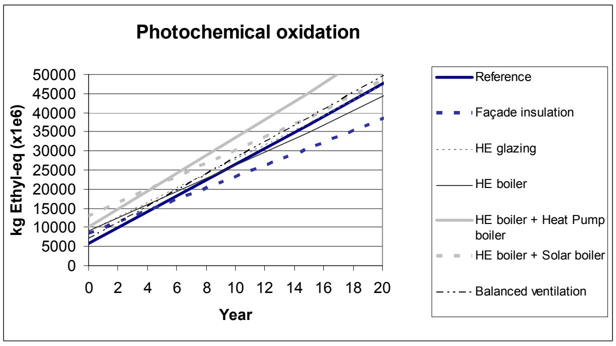
The results for all environmental effects are shown in figure 5, in which the environmental effects caused by the embodied and operational energy and material use over 30 years are plotted. Because the different environmental effects are expressed in different units, they were normalized to 100% for the reference dwelling. Noticeable are the poor performances of variants 4 (heat pump boiler) and 6 (balanced ventilation), except for abiotic depletion and to a lesser extent for global warming and eutrophication. Also for the other variants the positive effect of the renovation measures appear to be lower than the primary energy use indicated. However, insulation measures (variants 1 and 2) lead clearly to less environmental effects than the other variants. Insulation and replacement of the conventional boiler by a high efficiency one result in less impact for all environmental effects.

Figure 6 shows the environmental effects resulting from the operational energy use only (embodied energy and materials are excluded). To make comparison with figure 5 possible, all environmental effects, including those of the reference, were normalized with respect to the 100% value in figure 5. Comparison between figure 5 and figure 6 shows that the operational energy use contributes for a very large part to the environmental effects abiotic depletion, global warming and eutrophication. The contribution of embodied energy and embodied materials is minimal for these effects, but they clearly play a much more important role in all other environmental effects. This means that the environmental optimization of materials used for heating and ventilating equipment is important, because their effect on ozone layer depletion, photochemical oxidation, acidification and all toxicity items is substantial, and after 30 years, still far from negligible. Particularly important seems the optimization of the solar boiler, whose poor performance arises in large measure from material use (steel vessel).

However, most of environmental peaks in figures 5 and 6 come from the operational energy use. Variants 4 and 6 cause a particularly high worsening (up to more than 3







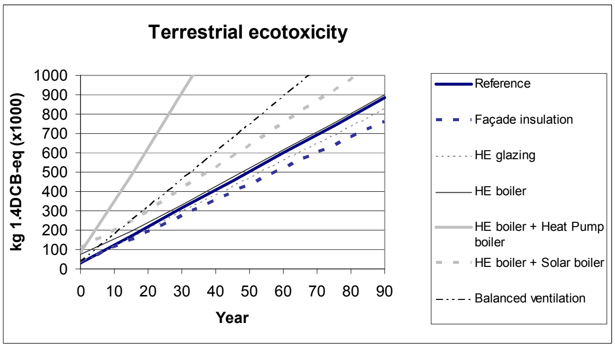


Figure 4: examples of the course in time of cumulated environmental effects.

times the environmental effect of the reference) for six of the ten effects studied. This worsening is directly related to the increase of the electricity use in comparison with the reference. Electricity is used in variant 4 for the heat pump boiler and in variant 6 to power the ventilators for the balanced ventilation. The increase in environmental effect is caused by the switch from gas use to electricity use. Due to the actual Dutch average fuel mix for electricity production (30% oil, 5% coal, 50% gas, 10% nuclear and 5% renewables), a very limited change-over from gas demand to electricity demand causes a substantial increase of the environmental effects ozone layer depletion, photochemical oxidation, acidification, humane toxicity and ecotoxicity.

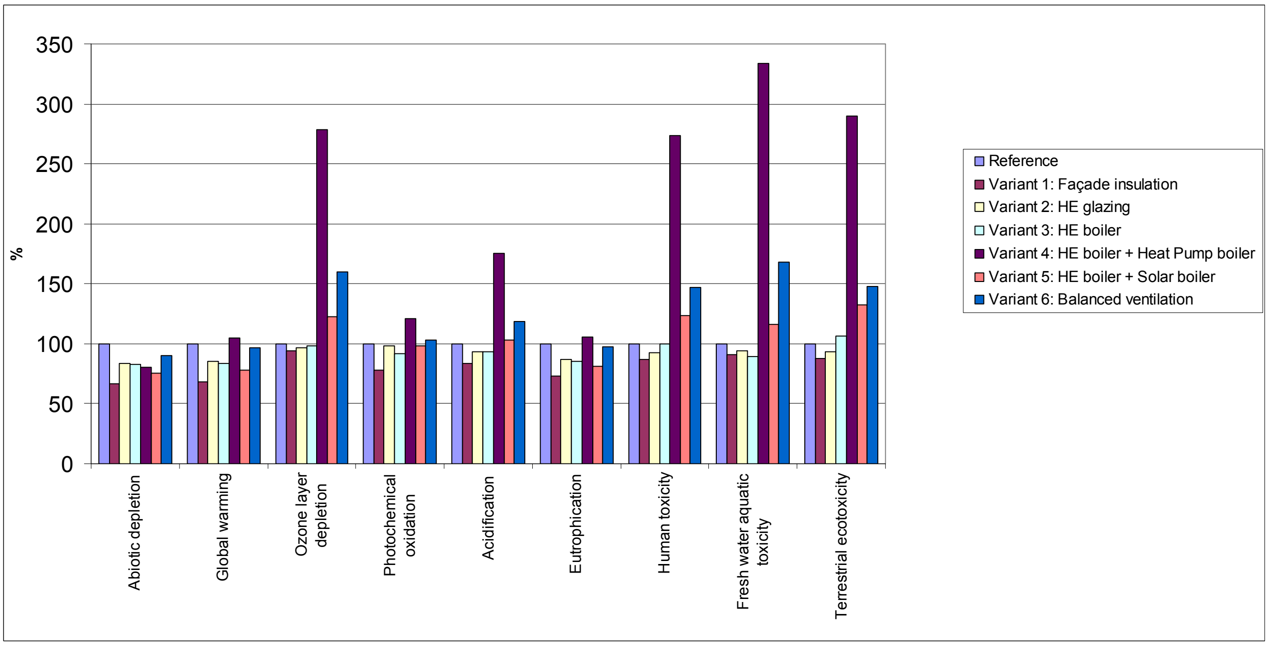


Figure 5: Environmental effects from embodied and operational energy and material use after 30 years.

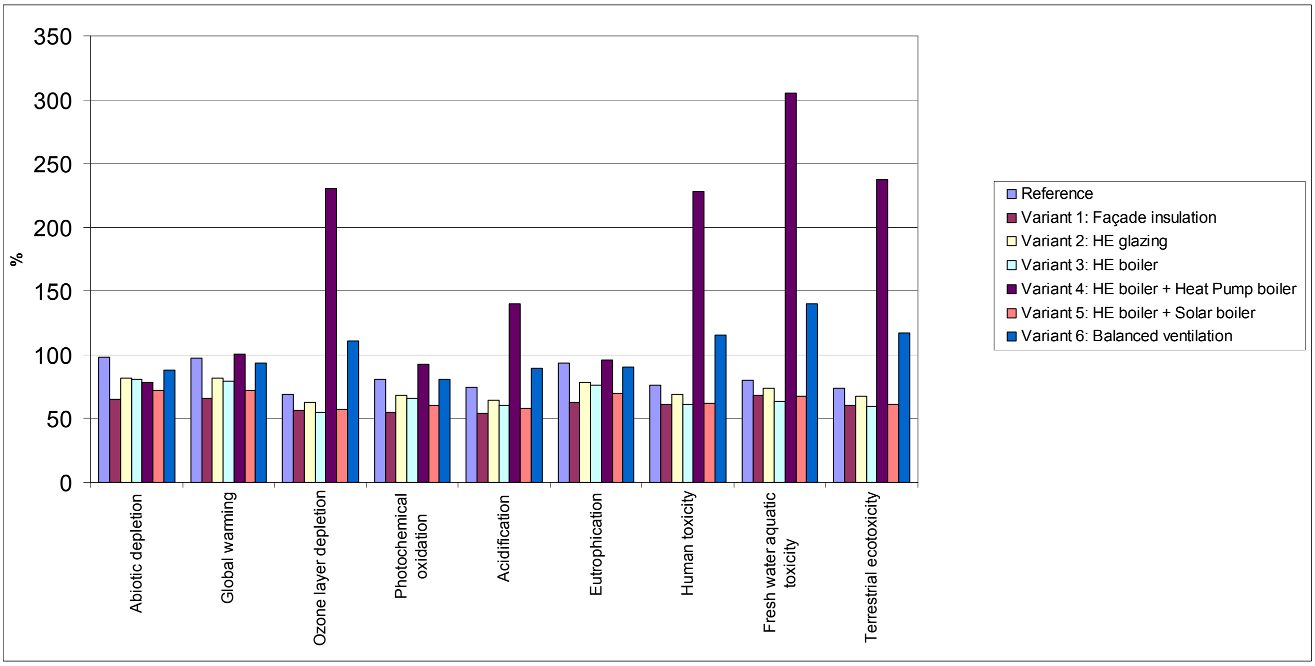


Figure 6: Environmental effects from operational energy use after 30 years.

An unfair conclusion would be that heat pumps should not be used because they increase the environmental burden. The right conclusion is that heat pumps should not be used if they are powered by a conventional electricity plant. Conventional gas is likely to have reached its limits with the high efficiency boiler. By contrast, heat pumps can achieve a much higher efficiency and have a high improvement potential. The use of electricity produced by a more sustainable fuel mix, or better, renewable sources, is a requisite when applying heat pump technology.

4.2 New-built

Similar calculations were conducted for the Ecobuild dwellings (see section 3) and are presented in figure 7. The analysis leads to the same conclusions as for renovation.

5 CONCLUSIONS

This paper compared the primary operational energy use for heating of several renovation and new-built variants with the primary energy embodied in the variant itself. It was found that after 30 years of use, the embodied energy in renovation variants is very low, opposite to the embodied energy in "low-energy" new-built that can amount up to 60 years of operational energy use. This means that the further reduction of the environmental impacts of dwellings will necessitate the reduction of their embodied energy use.

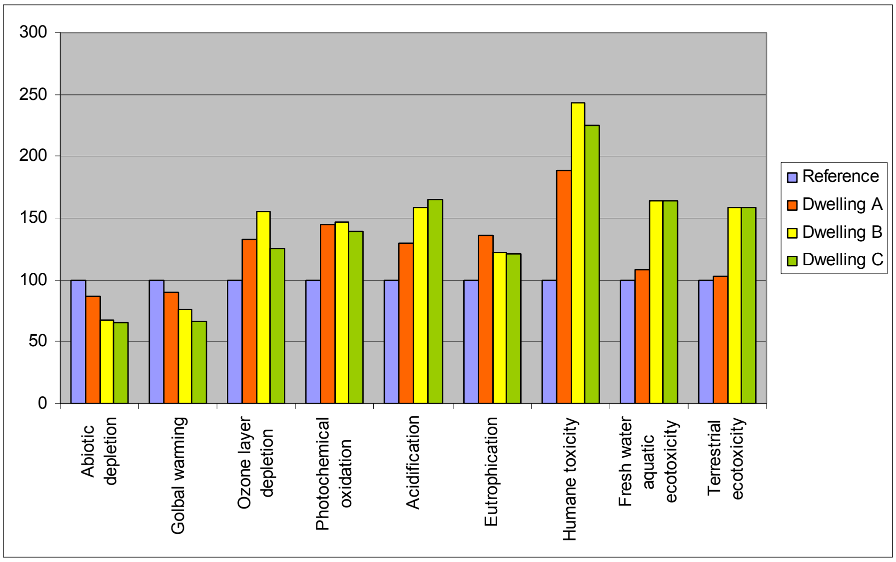


Figure 7: Environmental effects of the Ecobuild dwellings after 75 years.

However, energy use is not an environmental effect, but the cause of several environmental damages. The paper demonstrated that the primary energy use renders reasonably abiotic depletion, global warming and eutrophication. For the other environmental effects (ozone layer depletion, photochemical oxidation, acidification, humane toxicity and ecotoxicity) the primary energy use is not representative for the real environmental impact, especially when there is a shift from gas demand to electricity demand. That is the reason why heat pump boilers and balanced ventilation perform poorly. This cannot be solved without switching to sustainable electricity production. Insulation measures appear to be efficient for all environmental effects.

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Research Framework for an Experimental Study on Phase Change Materials in Scaled Models of Dutch Dwellings

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Abstract

In modern Dutch dwellings, about 10% of the annual use of primary energy is used for cooling, whereas about 50% of the primary energy is used for heating. With the technology of Phase Change Materials (PCMs) energy savings can be made in both areas. PCMs are materials with a high latent heat capacity which are, by melting and solidifying at a certain temperature, capable of storing and releasing a certain amount of energy. Unlike sensible storage materials, PCMs absorb and release heat at a nearly constant temperature. At hot days the PCMs can store (part of) the excessive heat to form a (temporarily) buffer. The heat is released again when the temperature drops below the melting temperature of the PCM. As a result, people inside a building incorporating PCMs can experience more comfort than in conventional buildings.

To measure the possible energy savings, an experimental research facility was set up. In this field set-up, modern Dutch dwellings are simulated by using scaled models with and without PCM in the concrete floors. These models are provided with sensors measuring the inside temperature and the incoming solar irradiation. As a reference, a weather station collects data on the outside temperature, humidity, solar irradiation and wind speed. By comparing these data, the influence of the PCM's becomes apparent.

In this proposition paper, a research framework to analyse the influence of PCM will be presented. To provide models, software packages will be assessed. The software package, which must be able to calculate the thermodynamic differential equations dynamically, will visualize the incoming and outgoing energy flows. The results, regarding the effectiveness of PCM, will also be implemented in the computation methodology of the Energy Performance Coefficient (EPC).

Keywords:

Phase Change Materials, Built Environment, Solar energy, Energy Savings, Experimental Research

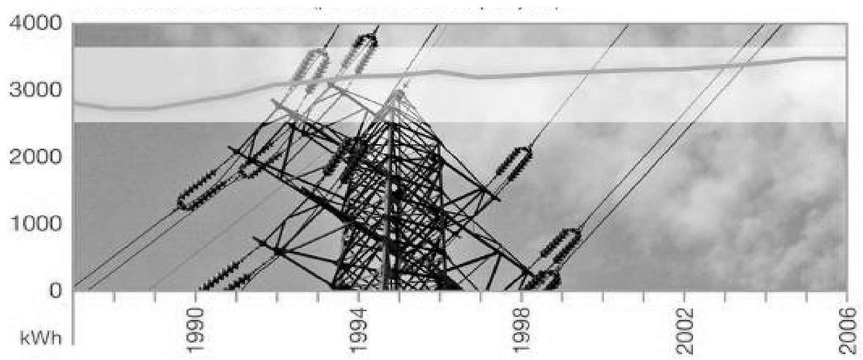

Figure 1 : Increase of annual electricity consumption in Dutch households, per household [1]

1 INTRODUCTION

Nomenclature

A_{gs}	Total ground surface [m^2]
A_{ts}	Total thermal transmission surface [m^2]
C	EPC Correction factor
E	Energy [J]
J	Joule (MJ = MegaJoule)
K	Kelvin
k	Thermal conductivity coefficient [W/(m·K)]
L	Thickness of wall [m]
m	meters
Q_{total}	Annual primary energy use of a house [MJ]
$\dot{Q}$	Heat density [W/m^3]
$\vec{q}$	Heat flux [W/m^2]
S	Surface of integration
s	seconds
T	Temperature [K]
t	Time variable [s]
u	Internal heat per volume [J/m^3]
W	Watts
x, y, z	Spatial variables for direction [m]
in	Subscript for inside
out	Subscript for outside

Because fossil fuels will probably not available forever, the world nowadays deals with energy saving. With still increasing demands, one is, as a result, becoming more interested in being energy efficient. Man can see this trend for example in the electronics branch, like with computers, laptops and mobile phones.

Although better technologies, smarter designs and a growing awareness and interest in energy results in better energy efficiency, an average Dutch household still uses more and more electric energy, which can be seen in Figure 1.

There are several reasons for this increase. The most important one is an increasing number of household appliances. Especially the amount of dryers, dishwashers, small electronic devices and the usage of computers increased during the last decade [1].

Another reason is the decrease of habitants per dwelling. This will result in higher electricity consumption per household, because a single person household uses about one-third more electricity than a household with two persons uses. Also, on average, a household with either one of a double-income couple will use more electricity (because they tend to have more timesaving appliances) compared to households with persons who are often at home [1].

A third reason is that many household appliances stay in stand-by mode more often these days. This seems to be underestimated, because most people apparently think they do not use that much more electric energy. Also some electric devices consume electric energy even when the power button is turned off.

A last reason is the increasing demand for cooling during summer times to increase human well-being. A Phase Change Material (PCM) can contribute to human well-being.

PCMs form a relatively new and promising technology that may both decrease the electricity consumption during summer times ("space cooling", see Figure 2) and the energy needed for heating the building. These materials are capable of storing heat temporarily and therefore save on cooling demand.

This paper will present a research framework [3] to analyse the influence of a PCM in a concrete floor in a Dutch climate. After this introduction, section 2 starts with a theoretical background of PCM. The physical principle, the possibilities and the applications of PCM will be explained here and an overview of different types of PCM will be given.

In section 3 the problem definition and some research objectives will be formulated. It also gives an indication of where PCMs can have a positive effect on the image of the building industry nowadays. The impact of this research will be further clarified in sections 4 (societal and scientific relevance).

Section 5 shows the experimental set-up which will give an answer on the research question. This set-up consists of four test boxes, with different glazing insulation and absence or presence of PCM in the concrete floor. It explains how this set-up is built and where it is located.

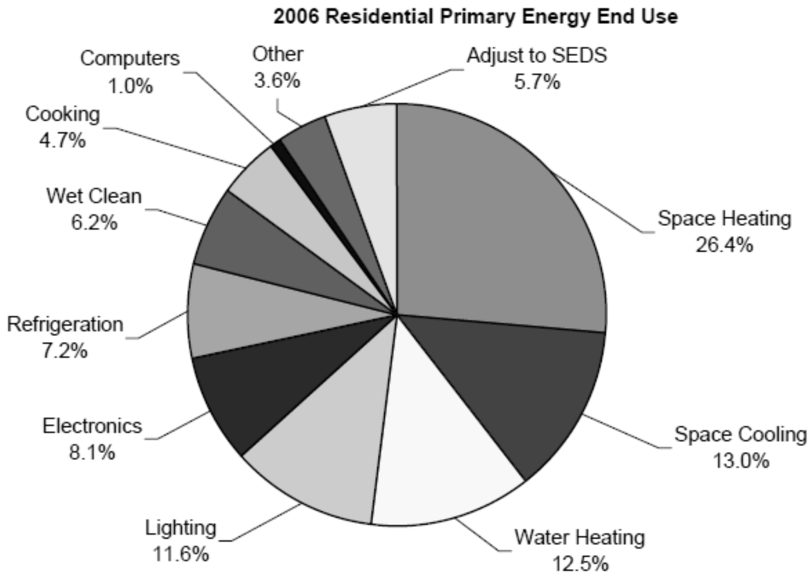

Figure 2 : Primary energy use of U.S. households [2]

The research methodology will be explained in section 6. This section will give a stepwise route to answer the research question. Also some interesting software packages will be discussed here.

In section 7 a summary of the research so far will be given as well as some points of interest for further research. Briefly some preliminary results will be given.

2 THeoretical background

2.1 What is a PCM?

When a solid material is getting heated, its temperature is raising. If the amount of heat is large enough, the solid will start melting. At that point, during the melting process, the temperature will stay constant[2] and the thermal energy is absorbed by the material.

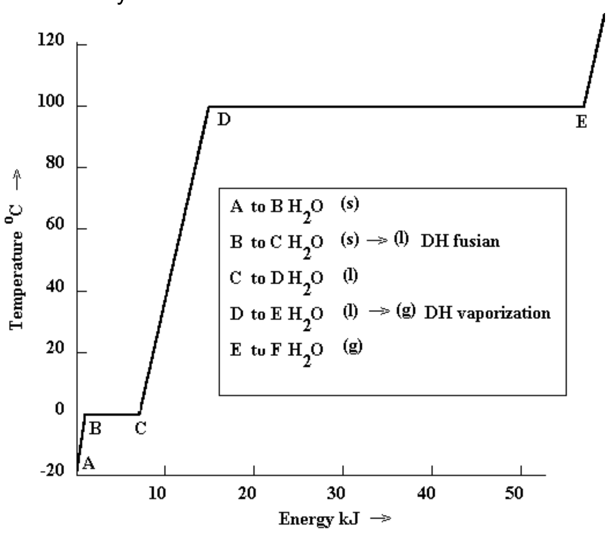

Figure 3 : Latent heat, from B to C and from D to E of water

In Figure 3 this is trajectory B-C. By absorbing this so-called latent heat, a *temporarily* buffer of energy is formed. The temperature will increase again if the material is totally molten and does so until it reaches its boiling point. Then the same process happens again: temperature during the phase change stays constant[1]. When the material is cooled down, the process will take place in opposite direction.

A PCM behave like this physical principle, but unlike conventional (sensible) storage materials, PCMs absorb and release heat at a nearly constant temperature. They store 5–14 times more heat per unit volume than sensible storage materials such as water, masonry, or rock [4]. Thus PCM is a material that is capable of storing latent heat and therefore might improve the total heat capacity of the internal constructions. As a result, people inside a building incorporating PCMs can experience more comfort than in buildings without PCMs.

2.2 PCM: Classification, Properties & Applications

Several materials can be suitable as a PCM that is capable of saving energy in the built environment. There are both organic and inorganic substances as well as a mixture of organic and/or inorganic substances with different melting points; the eutectics. The organic PCMs can be separated into paraffins and non-paraffins, whereas the inorganic PCMs can be separated into salt hydrates and metallics. Figure 4 gives an overview of the different sorts of PCMs [5].

The organic PCMs have some physical advantages over the inorganic and eutectics PCMs. They have a broad temperature range and because of this, selection of the right organic PCM is easier. Organic PCMs are highly compatible with conventional materials of construction; they are chemically stable, safe and non-reactive. The downside of organic PCMs is their higher costs.

If investment is the criterion, one should opt for an inorganic PCM, which is also easier available [5]. The downsides of an inorganic PCM are that the change of volume due to temperature differences is very high and that they suffer from decomposition and supercooling, which can affect their phase change properties.

[1] This is true if the solid material consists of only one type of molecules.

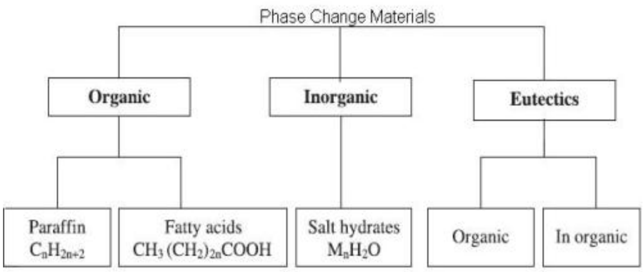

Figure 4 : Classification of PCMs [5]

Most of the PCMs that were used in the built environment for thermal storage in conjunction with both passive storage and active solar storage for heating and cooling in buildings, have melting temperatures between 20-32ºC [6].

There are two purposes for using PCMs in buildings. Natural heat (that is solar energy) can be used for heating or night cold for cooling. Or manmade heat or low temperature sources can be the reason for installing PCMs. In any case, storage of thermal energy is necessary to match availability and demand with respect to time and also with respect to heating and cooling capacity. Basically three different ways to use PCMs for heating and cooling of buildings are [6]:

1. PCMs in building walls;
2. PCMs in other building components other than walls; and
3. PCMs in heat and cold storage units.

The first two are passive systems, where the heat or cold stored is automatically released when indoor or outdoor temperature rises or falls beyond the melting point. The third one is active system, where the stored heat or cold is in containment thermally separated from the building by insulation. Therefore, the heat or cold is used only on demand and not automatically [6].

2.3 Heat Transfer & Energy Balance

On a clear day, solar irradiation heats up the building shell. By means of conduction this heat is transferred through the walls and by means of mainly convection it finally heats op the room inside. If steady state can be assumed and the supplied heat is constant through a constant cross-cut, the temperature of the room inside is calculated with:

$$T_{in} = T_{out} - \vec{q} \cdot \sum_{i=1}^{n} \frac{L_i}{k_i} \qquad \text{(Eq. 1)}$$

In this formula the sum interprets the different surface layers with different thicknesses and different thermal conductivities. But this only holds for steady state situations. In real world this is never the case, for example because irradiation is never constant and therefore the produced heat from the sun is not constant over time. Another example is the influence of the wind blowing over a surface. Both its speed and direction is never constant, making calculations and predictions very difficult.

Prediction of the 3D temperature profile in this room then is based on the standard heat equation. Suppose a PCM will be used as a passive system in this room. When it comes to internal heat generation, due to melting or solidifying of the PCM, the (extended) heat equation becomes:

$$\frac{\partial u}{\partial t} = k\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) + \dot{Q} \qquad \text{(Eq. 2)}$$

In which the added '$\dot{Q}$' represents the internal heat density [W/m^3] of PCM.

The energy balance for such a system can then be formulated as:

$$\frac{\partial E_{in}}{\partial t} - \frac{\partial E_{out}}{\partial t} = \int_S \vec{q} \cdot \overrightarrow{dS} \qquad \text{(Eq. 3)}$$

In this formula, the integral represents the time rate of change of the total amount of accumulated energy. The formula holds for passive PCM systems only, because a passive PCM system can only exchange energy with its surroundings through heat transfer.

3 Problem definition & research objective

The Dutch building industry is a rather conventional industry. Although there are high demands and there is a trend of being innovative, the overall image of the Dutch building industry is not very good [7]. A good example of this image is the traditional concrete and brickwork style of Dutch dwellings. Basically, on the building and construction aspect of dwellings, there are not very much changes in the last decades compared to Germany, in which houses with different building shells are more common. The downside is that one have to find other techniques to reach the energy-efficiency goal. With the niche of PCM the Dutch concrete and brickwork style can be maintained, whereas the energy-efficiency of these materials can be increased in a simple way.

The planned research is aimed to give insight in the energy saving possibilities of PCMs in the Dutch building sector as well as presenting a simulation model that visualize the energy flows within such a dwelling. In this way the planned research can be divided into a main research question and a sub research target.

The main research question can be stated in the following way:

Table 1 : Building physical constitution of the test boxes in the experimental setup [10].

	Test box A	**Test box B**	**Test box C**	**Test box D**
Insulation material (thermal resistance)	Cellular glass 3.8 $(m^2 \cdot K)/W$	Cellular glass 3.8 $(m^2 \cdot K)/W$	Light multilayered 5.6 $(m^2 \cdot K)/W$	Light multilayered 5.6 $(m^2 \cdot K)/W$
Phase Change Materials in concrete floor (weight percentage)	Present ± 5%	Absent 0%	Present ± 5%	Absent 0%
Thermal resistance glazing (thermal transmittance)	High 1.1 $W/(m^2 \cdot K)$	Low 0.5 $W/(m^2 \cdot K)$	High 1.1 $W/(m^2 \cdot K)$	Low 0.5 $W/(m^2 \cdot K)$

"What is the influence of using PCM in the Dutch built environment and what is the influence of PCM on the Energy Performance Coefficient (EPC) of a standardized Dutch dwelling?"

To answer the research question a research facility at the University of Twente is set up. This facility will give a practical answer, based on measurements. This will be further described in section 6.

The sub target is aimed at modelling. Modelling is necessary for monitoring purposes and to visualize the energy flows within the model. To calculate a theoretical lowering of EPC, the simulation model can be used and the results can be compared with the found experimental data. In a later stadium the temperature boundary conditions can be coupled with climatologic data, to predict energy savings at any place.

Because making a simulation model of real test objects involves combining differential equations from heat transfer and turbulent media, a software package that can handle this should be found. The sub target can be summarized in the following way:

Visualize energy flows within the simulation model by using a software package that is able to calculate with differential equations from heat and mass balances, using the finite element method.

The results of the model are verified with the experimental data.

4 societal & scientific relevance

In March 2007 the European Union (E.U.) leaders agreed on the renewable energy target. All the 27 E.U. member-states will each decide how they contribute to meeting a 20% boost overall in renewable fuel use by 2020. Also the member-states will cut their carbon dioxide emissions by 20% from 1990 levels by 2020 [8]. The EU plan involves:

- A 10% minimum target on the use of bio-fuels in transport by 2020;
- A commitment to increase use of solar, wind and hydroelectric power;
- A possible ban on incandescent bulbs, with filaments, in offices, street lights and private homes by the end of the decade [8].

The plan does not mention energy saving, which can greatly reduce energy consumption and therefore make those targets less difficult to reach. For example, the Netherlands have 2.31% (2005 figure) of their primary energy consumption from renewable energy sources. Their target is 14% in 2020 [9]. This requires a major step of improvement regarding less energy consumption, better energy efficiency and a big step forward into sustainable energy sources. Actually, it seems quite impossible to reach this target without saving on fossil fuel consumption.

Starting from 2006 the Dutch Building Code requires dwellings to be made with an EPC of 0.8 or less.

The EPC is introduced for new residential buildings starting from the end of 1995. The EPC is a result of an integral energetic assessment of a building and its installations made during the design phase. It is a index that can give an indication of the energy efficiency of a new building. The EPC for new residential objects is calculated as follows [10]:

$$EPC = \frac{Q_{total}}{330 \cdot A_{gs} + 65 \cdot A_{ts}} \cdot \frac{1}{C}$$

(Eq. 4)

The EPC takes only energy used to heat and cool the building (and water) and energy consumed by lamps into account. For heating up the building a reference climate model is used.

Energy consumed by household appliances is not taken into account. Therefore the energy consumed in reality is higher and the EPC cannot be used to 'predict' the energy bill.

Because of the international energy agreements, the Dutch will further reduce the EPC level to 0.4 in 2015. This means that 50% of the primary energy used for buildings energy should be saved. PCM can provide in less energy consumption and can be a good way to lower the EPC. Lowering the EPC means it is an attractive way to reach the required EPC goal, provided that it is economically feasible. Implementing PCM in the traditional Dutch building industry is a good way to reduce on fuel consumption.

5 experimental field set-up

At the Campus of the University of Twente four models are made, called test boxes, that differ in kind of insulation and presence of a PCM in the concrete floor. In this experimental field set-up a mixture of paraffins in powder form encapsulated in polymethyl methacrylate microcapsules is used. It has a melting point of 23°C [11] and the PCM is used as a filler in concrete. Therefore one will not see any differences compared to normal concrete. In Figure 5 one can see an impression of these test boxes and in table 1 one can see the different types of insulation that are processed [12].

Figure 5 : The four test boxes on top of a sea container, after the third one a weather station is visible

The size of the test boxes is scaled to about 1.35 m by 1.10 m (l × w). The scaled dimensions result in a 115 times smaller air volume and a floor surface that is thirty times smaller compared to a standardized Dutch dwelling. It is expected that the influence of this down scaling is relatively small, because the mass of air and heat capacity per kilogram are low compared to the mass and heat capacity of the floor [12].

As can be seen in figure 5 the test boxes all have at one side a window consisting of 0.36 m^2 glass. Nowadays it is normal to use double glazing with an U-value of 1.1 W/(m^2·K). This is used in two of the four test boxes. The other two consists of triple glazing, having an U-value of 0.5 W/(m^2·K).

Another difference is the insulation and materials used in the sides of the test boxes. Because of practical advantages cellular glass with a thermal resistance of 3.81 (m^2·K)/W, is used in two test boxes. The other two test boxes have a light form of insulation, having a thermal resistance of 5.6 (m^2·K)/W, when taking a cavity of 20 mm into account.

The last difference between the test boxes is the presence of PCM in the concrete floor. Two of them have PCM present.

The test boxes are installed on the Campus terrain of the University of Twente located in Enschede, The Netherlands. They are placed outdoor on the roof of a sea container (2.55 m height) to avoid disturbances and to prevent unwanted shading. The test boxes are packed with temperature sensors and two test boxes can measure the solar irradiation. A separate weather station collects weather data every five minutes, containing outside temperature, solar irradiation, humidity, wind speed and wind direction.

6 research methodology

Now with the research question in mind, how to find an answer on it? The research methodology will be separated into some major steps.

Because this is an experimental research, the first step is finalizing the research facility and getting insight of the computation methodology of the EPC. At the point of writing, saving weather data, for example, is still troublesome. This is a preparation step that still has to be done. After finishing this step, it should be possible to generate and save weather data automatically.

The next step is finding a useful software package for the modelling. There are three different candidates: COMSOL©, ANSYS© and TRNSYS©. Key points will be pricing, model accuracy and hardware requirements. All the three packages have their own advantages and

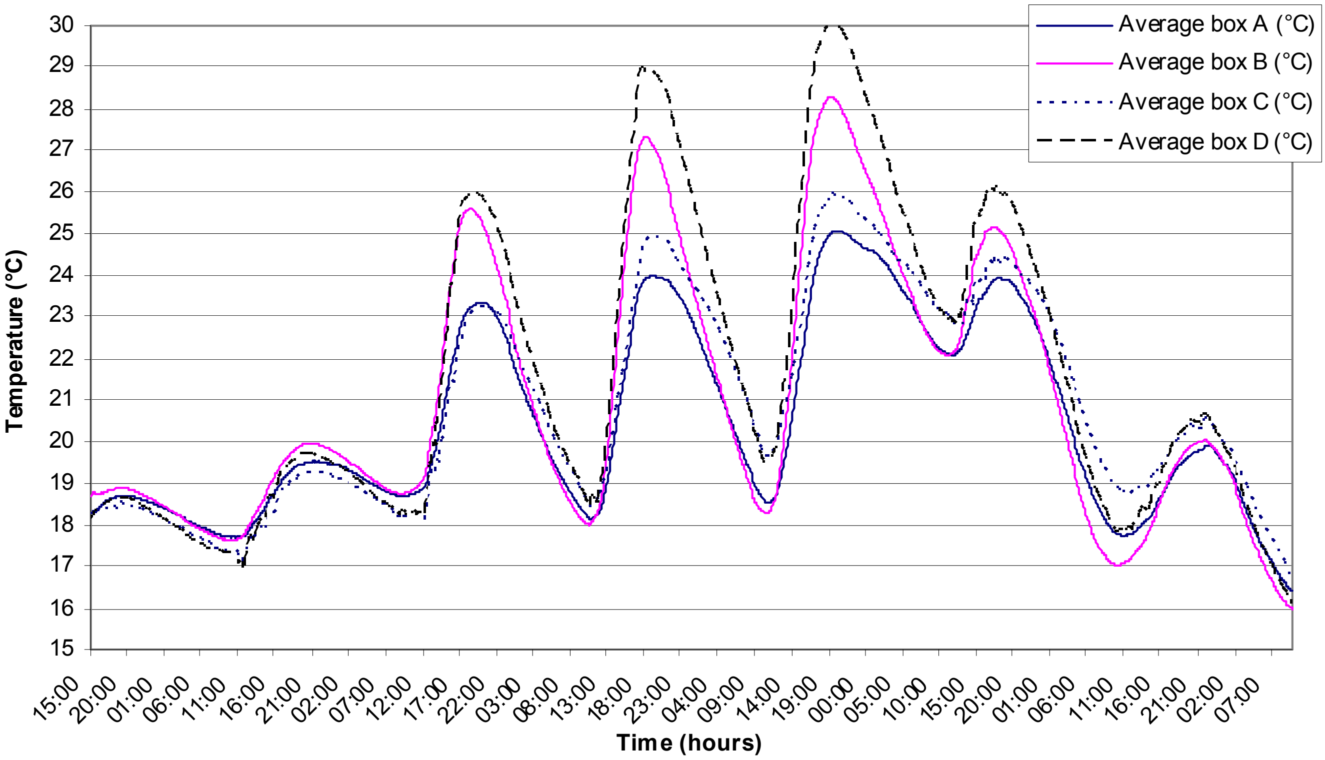

Figure 6 : Temperatures of the four concrete floors from 8-27-2008 15:00 till 9-3-2008 09:45 [12]

disadvantages. At the point of writing the COMSOL© package seems to have an advantage, because it can handle partial differential equations from both the energy field as well as the aerodynamics field together. This will enhance accuracy and speed up the calculations.

Also, synchronously, weather data will be collected and comparison between the different test boxes will take place. This will give a qualitative insight in the energy saving possibilities of the different test boxes.

After finding the right software package, the third step is to find an answer on the question: "What information (variables, constants/properties and formulas) do I have and what of this information is of importance?" So a clear picture of all the relevant physical effects have to be made. What phenomena are relevant to be modelled? What assumptions will be made? And what side effects can be neglected? Because of the complexity and importance of this step, a lot of attention will be paid on the requirements and specific configuration.

The fourth step is the drawing of the test box. If the geometry of the test box is too complex for the found software package, a 3D CAD software package will do the job. Nowadays all commercial CAD packages are able to export shapes to other software. After importing this shape into the found software package, boundary conditions can be set. This will be done with the assumptions made in the third step. Now the program is ready to solve the heat problem and give data about energy, temperatures and pressures.

The fifth step is comparing the temperatures from the simulation model with the real experimental temperatures from the test boxes and the weather station. Where are the differences? How can they be explained? And how can the boundary conditions be changed to give a fairer (compared to the real world) solution.

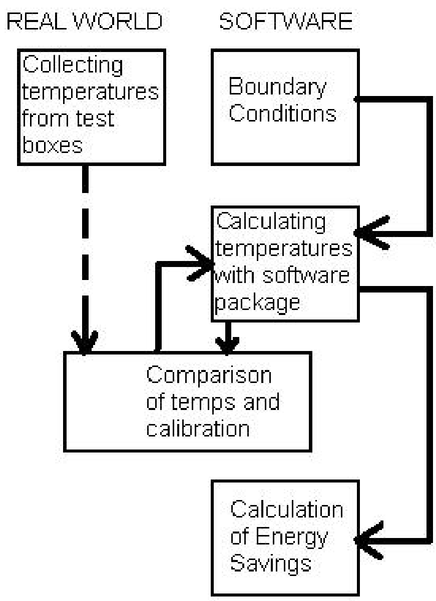

Figure 7 : Visualisation of step 5

In this step also an answer should be given on the question: *How much* energy can be saved on a yearly basis with PCM in concrete in the Netherlands? If the boundary conditions are changed in such a way that the calculated temperatures are quite close to the real temperatures, the found software package is able to calculate the energy savings due to the presence of PCM. An overview of this step can be seen in Figure 7.

The last step is making an official document that describes the lowering of the EPC by using PCM in Dutch dwellings. Here information from step one will be used.

7 DISCUssion & further research

This research proposal is focused to give a practical, but quantitative, answer on the energy saving possibility of PCM in concrete in a Dutch climate. The PCM in the experimental set-up is chosen in such a way that its saving potential is as high as possible for a Dutch situation. An important thing to realise is that PCMs store heat only temporarily and the question arises for how long it can store its heat. If the temperature is above the melting temperature of the PCM for such a long time that the PCM is able to melt completely, the net energy saving due to the PCM itself is zero. In southern Europe for example, it is expected that the energy saving potential is *relatively* lower, because of this effect. As a result a different PCM will be chosen there, with a higher melting point.

Some preliminary effects of PCMs can already be given, because the weather station and the twelve temperature sensors inside the test boxes have already been collecting data. The sensors are equally distributed among the four concrete floors.

Figure 6 shows the average temperatures of the floors per test box from 8-27 15:00 till 9-3 9:45. As can be seen, test box A and C, each containing PCM in the floors, have lower peak temperatures than test box B and D, which do not contain any PCMs [12].

There are only big differences when the maximum temperature is raising above 23°C, so the PCM can absorb the surrounding heat by melting, temporarily avoid further increasing temperatures. The figure also suggests that the presence of PCM is of more importance for saving energy than the type of insulation. Whether this is really true cannot be concluded from data of only seven days.

Further research will show how much energy can be saved practically and what kind of energy can be saved. It is expected that most energy that can be saved is electricity, because lower peak temperatures means lower cooling demands.

8 acknowledgments

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The Jerusalem Eco-Housing Project - Applying Integrated Design Solutions

Gil Peled – Architect, MSc., Project initiator

ABSTRACT

The existing housing stock in Israel consists of some 2 million dwellings in multi-storey residential buildings. Nearly half of them were constructed 50 years ago or more, and require extensive refurbishing to current standards and reduction in their harmful emissions. The Jerusalem Eco-Housing Pilot Project, the first of its kind in Israel, consists of the renewal of a typical apartment building focusing on sustainable and affordable improvements to the building's structure with occupants' participation in the process. The purpose of the project is to demonstrate best practice including specifications and procedures which can be widely implemented to improve the environmental performance of the existing building stock. For this, an integrated design strategy has been developed, addressing energy efficiency, water conservation, use of materials, waste reduction, transport, occupants' wellbeing, health and safety, urban ecology, and disaster control. The following paper describes the current status of the project and the applied integrated design solutions.

KEYWORDS sustainable, housing, integrated design, Jerusalem

1.0 INTRODUCTION

1.1 Rationale

Some 70% of the existing housing stocks worldwide will exist in 30 years from now. During this time ecologies at all scales will be pushed to the brink due to: substantial growth of world population, an increase in resources required to support it, a substantial rise in urban pollution, a decrease in land available for new build increasing pressures and demands on opens space. This situation, with its local variations and complexities, is a growing challenge worldwide, becoming more acute with the growing political, economic and environmental uncertainties.

Israel's population of over 7 million is living in an estimated 2 million dwellings situated mostly in urban areas. Nearly half of these were constructed 50 years ago or more, and require extensive refurbishing to current building standards and reduction in their harmful emissions. Despite nearly 50% of the country's natural resources being used for construction operation and refurbishment of buildings, so far, none of the public or privately initiated housing refurbishments have addressed sustainable issues in systematic and comprehensive manner; moreover there are practically no incentives to improve this situation. To date the housing stock is a major pollutant, in its daily use, refurbishment and decommissioning, and is also a major contributor to the 7% annual increase in household electricity and water demands, hence the need for widely applicable sustainable solutions.

1.2 Project description

Figs.1&2 The Pilot Building (photos Gil Peled)

The Jerusalem Eco-Housing Pilot Project, representative of at least 300,000 countrywide, is a typical multi-storey residential building which has concluded its first life cycle of 50 years and is in need of renovation.

The project, the first of its kind in Israel, situated near the city centre and the historic Old City of Jerusalem, consists of retro-fitting the building according to sustainable principles.

Starting at the basic building blocks, the building and the household, the project treats the building and its immediate environment as a whole, with the overall aim to create specifications and procedures which can be applied widely by replication, to significantly improve the environmental performance of the existing housing stock in Israel.

The projects objectives include:

Reducing the environmental footprints of the building and its occupants,

Regenerating an existing building applying sustainable and affordable measures,

Documenting implementation process and footprint reductions,

Determining feasibility and ROI for potential for replication,

Raising awareness among private and public stakeholders and the wider public.

Two parallel processes are ongoing: the physical renewal of an apartment building, focusing on the communal areas, and the education and enhancement of the eco- awareness of its inhabitants, focusing on the households.

1.3 The existing building

1.3.1 The physical structure

Plot size (incl. garden)	577.00 m2	Total built up area	606.80 m2
2 room apartments (8)	50.00 m2	Total private areas	502.50 m2
1 room apartments (2)	26.00 m2	Total communal areas	611.35 m2

Construction method	Concrete and limestone cavity walls, concrete floors
Indoor finish	Plaster and paint, terrazzo tiling, wooden openings
Space heating system	Mostly electrical radiators, some air-conditioning
Water heating system	Mostly electricity powered. 50% solar panels
Health and safety risks	Asbestos content, condensation on walls, etc.

Table 1: The pilot building's specifications

1.3.2 The social structure

The 21 person multi-generational occupancy, comprises young families, pensioners, and singles in owner-occupied and rented apartments. The project has created a dynamic social network with an understanding of the benefits everyone can gain from this process. Occupants are involved in auditing and monitoring of their energy and water consumptions in their households with each of them focusing on areas of special interest to them and sharing experiences between them. Informal gatherings in the communal stairwell or garden are the common way of exchanges of information advice and support. The project has also enhanced the participation of occupants in joint activities and decision-making regarding upkeep of the building.

1.4 Key issues and targets

The key issues addressed include: energy efficiency, water conservation, waste reduction, use of materials, alternative transport, occupants' wellbeing, health and safety, urban ecology, disaster control, eco-awareness.

The targets include: an initial 20-30% reduction in overall energy, water and waste emissions both in communal areas and individual households, improving environment, health and wellbeing, eliminating health and safety hazards, improving accessibility and improving building aesthetics. For example: we have achieved so far a 30% reduction in household waste, about 3 tons annually. If such a reduction were to be achieved in the refurbished housing stock an annual reduction of approximately one million tons would be possible (300.000 buildings x 3 tons). Significant reductions would also be possible in carbon emissions, water consumption etc.

2.0 INTEGRATED DESIGN

2.1 Design Strategy

No existing strategy was known to us at the outset for a retrofit pilot project, however our intention was to treat the building as a whole. A multi-disciplinary approach was adopted, integrating aspects of sustainable housing, environmental management, Local Agenda 21, eco-footprinting and public participation.

An initial survey of the building structure and of the occupancy composition was carried out, mapping out the issues requiring special emphasis.. Then a work plan for implementation of sustainable measures was set according to the identified issues (see table below).

2.2 Local factors

The local factors, which determine the integrated design and implementation of measures in a residential building in Israel include: climatic and seismic regions, dwelling sizes and densities, building structure and construction methods, dwelling ownership and maintenance type, ethnic, social and economic backgrounds of occupants.

Based on these factors, individual integrated design strategies can be set out for each and every building. For example: a residential building in Tel-Aviv may differ in construction method, earthquake resistance, maintenance, ownership and socio-economic character from a similar size building in Jerusalem, hence different strategies will be required.

2.3 Methodology

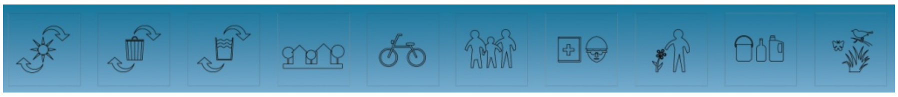

Fig. 3 The issues addressed, represented graphically (Gil Peled)

A CAD model is being created to quantify the resources used in its construction and to monitor the transformations taking place.

In addition a series of functional section drawings has been prepared which highlight the issues to be addressed such as energy efficiency and water conservation.

Overlapping the section drawings has turned out to be a simple way to identify interconnected issues requiring integrated design solutions, i.e. placing hot water pipes connected to solar panels in a way which reduces heat loss, improving the stairwell design etc.

A matrix table has been created on which these issues have been regularly updated and project progress documented. It includes columns for the required sustainable measures, options for their implementation, cost and benefits and estimated payback times.

Occupants' audits have enabled calculation of individual's energy and water consumptions as well as their ecological footprints. The baseline figures enable evaluation of their reduction and comparison with national averages, and with reduction levels achieved in similar projects worldwide.

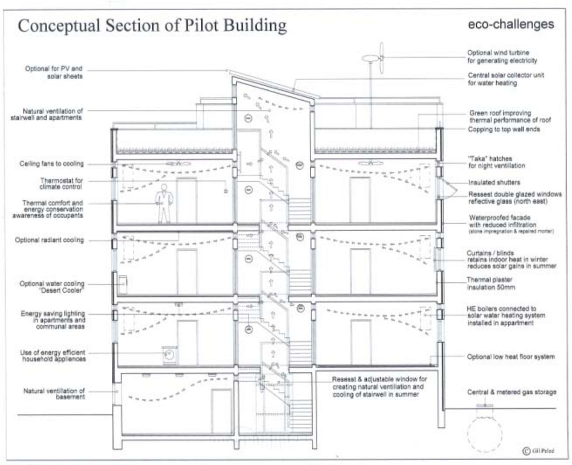

Fig. 4. An example of a functional section (Gil Peled)

2.4 Design Team

Ideally the design team of housing retrofit should have a continuous representation of all related disciplines and include consultants similar to those engaged in a new building i.e. architect, quantity surveyor, structural engineer, energy advisor and project manager.

The project manager, trained in Sustainable Housing Design, has coordinated the various issues with other consultants when needed. The project also encourages participation of occupants in activities and decision-making.

2.5 Feasibility

Overall implementation of integrated design in the pilot project has been borne by the occupants themselves over a period of five years We estimate that a total of some $2500 - $5000 will be required, equivalent to the value of less than 1 m2 of the apartment property value. Bearing in mind the environmental and physical improvements to the building and to the quality of life of its occupants this is money well invested, most of which will be returned. (payback time of 3-10 years). This investment is affordable and also feasible for the entire building stock.

3.0 STATUS OF INTEGRATED IMPLEMENTATION *

Issue	Method
Energy Efficiency	Energy saving lighting in communal areas & appartments Installing central underground gas storage tank (LPG) Waterproofing and insulating roof (phase 1)
Water Conservation	Restoring existing water cistern for irrigation Installing pump and computer drip irrigation system. Installing water saving devices in apartments
Waste Reduction	Recycling unit for batteries, bottles, textiles, paper Household organic waste unit for compost Retaining garden trimmings for compost
Use of Materials	Use of eco-friendly cleaning materials Clearing building waste from garden Reuse of building materials for new purposes
Alternative Transport	Creating a bicycle storage room in stairwell Mapping amenities within walking & cycling distance Encouraging use of public transport
Occupants' Wellbeing	Creating recreation areas in shelter and garden Adding indoor plants & improving thermal comfort Planting herbs for occupants' consumption
Health and Safety	Improving stairwell ventilation and smoke escape Replacing hazardous gas containers with safe storage Preparing a decommissioning plan for asbestos

Urban ecology	Installing nesting boxes on trees and netted fences Use of leaves as earth cover, mapping wild flora Creating a fruit and vegetable kitchen garden
Disaster control	Refurbishing bomb shelter to current standard Providing fire control and fire fighting equipment Review of building's earthquake resistance
Eco-Awareness	Enhancing occupants' participation & decision making Encouraging eco-friendly habits, audits and activities Preparing a carbon emission reduction scheme

***** The implementation in communal areas is the responsibility of the elected house committee and is subject to owner's consent and cost quotes. The implementation in individual apartments is carried out by the owners according to their needs and abilities.

Table 2: Current implementation status

4.0 EXAMPLES OF INTEGRATED DESIGN SOLUTIONS

4.1 The stairwell

The stairwell was open to winds at entrance level, with no entrance door, and was sealed off at the top. In winter it was cold and windy, and in summer hot air was trapped at the top cracking the top fixed windows. No smoke escape was provided, lighting was poor and disfunctional, and there was no sense of security. The integrated design solution included installing a recessed door with an adjustable window above it. Broken windows were replaced with new adjustable DG windows and a smoke escape was installed. In summer the door is in shade and the windows are open creating a natural cooling chimney effect. In winter windows are closed and the stairwell is heated by adjoining apartments. Energy efficient lighting has been installed providing better light. Under the stairs bicycle storage has been built and an area designated for recycle bins. The stairwell is now filled with plants and has become a secure environment and a social focal point of the building.

Fig.5 The green stairwell (photo Gil Peled)

4.2 The shelter

Over the years the shelter had fallen into acute disrepair. It could no longer be used for its original purpose and was full of old furniture and discarded items of previous occupants. It was a health and safety hazard. The integrated solution included decluttering and totally refurbishing the shelter, bringing it up to more current protection standards. Energy efficient lighting has been installed and water from the sink has been diverted to irrigate a part of the garden. The shelter has become a pleasant communal room which is used for activities of the occupants and as the Pilot Project office which will also house a small media centre.

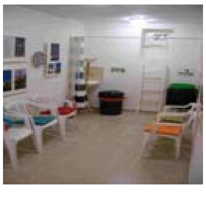

Fig.6. The refurbished shelter (photo Gil Peled)

4.3 The roof

The roof was in a poor state of maintenance, un-insulated and leaking. It was cluttered with old water barrels, pipes and broken solar collectors and antennas etc. It was a hazardous no-man's land The integrated design solution included removing the empty water barrels, waterproofing and partially insulating the roof. A plan has been set out for rearranging solar panels creating more space for additional ones as well as enlarging the access opening to enable use of roof for recreation.

Fig.7. The insulated roof (photo Gil Peled)

4.4 The garden

The garden surrounding the building was for many years a derelict area full of rubbish and building waste. Access was virtually impossible and it was a source of pests. Around the building was a ring of hazardous gas containers. No one in the building benefitted from it. The integrated design solution included mobilizing the occupants to take action and clean the garden and encouraging those living on the ground floor to open their balconies to the garden and to plant flowers. A path was laid around the building from old tiles found in a waste dump and a vegetable garden was created which is fertilized by compost created by the occupants. Gas containers have been replaced by a secure underground central storage. Rainwater is collected in winter and will be used to irrigate the garden in summer. The garden is now a pleasant and useful recreation space.

Fig.8. The rehabilitated garden (photo Gil Peled)

4.5 The individual apartments

Since the beginning of the project some apartments have been refurbished to varying degrees by the occupants. Some occurred while occupants have been resident, others before or after purchase by new occupiers. There has been monitoring of changes made and also suggestions made regarding installation of services. Bathrooms and kitchens were the focus of the refurbishments and some infrastructure has been put in place for future grey water recycling. A significant aspect was increasing the numbers of rooms while keeping the existing footprint. This allowed increasing value of apartment and a more efficient use of space in the given area. The refurbishment of apartments is process still in progress and pace is set by their occupants.

Fig.9. Installing water-saving fixtures (photo Gil Peled)

Fig.10 &11 Views of reclaimed garden and street elevation (photos Gil Peled)

5.0 FINDINGS

Throughout the progress of the project we have developed our holistic integrated design strategy and methodology. The employment of integrated design has streamlined results. Using functional section drawings and a matrix table has enabled the coordination of the sustainable refurbishment. The ongoing project has demonstrated the feasibility and affordability of various sustainable measures for widespread application in the existing housing stock. Occupants have responded well to this initiative, understanding that it benefits themselves as well as the environment. The project has generated significant interest at local and central government level as well as in the media. Crucial factors for its success and replicability remain availability of funds, incentives, working together of public and private stakeholders (PPP), and occupants' participation. The pilot project, the first of its kind in Israel, has already achieved most of its objectives, it is still underway and we hope it will inspire others in Israel and beyond

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The influence of changes in the physical and technical design on social

interactions in a cohousing community

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Abstract

Cohousing has gained renewed interest in the Netherlands, especially for populations of over 50 years of age and as an alternative for professional and family care. This in combination with living independently. In a cohousing community people have the possibility to share daily life activities in a specially developed facility. This paper presents the relation between changes in technical and physical characteristics and social interaction in a cohousing community. Based on literature and case studies gathered by students changes in social interaction through changes in the design of the cohousing community and home technology have been observed. Based on the results it was concluded that the relation between changes in the physical and technical context and social interaction occur in expected and unexpected ways. Changing interactions can be related to the script or to the change itself.

Keywords:

Social interactions, cohousing community, home technology, physical design

1 INTRODUCTION

Cohousing has gained renewed interest in the Netherlands, especially for populations of over 50 years of age and as an alternative for professional and family care. Together with the intention to live independently as long as possible. In a cohousing community people have the possibility to share daily life activities in a specially developed facility. These facilities comprise of multiple dwellings (20-30) that are oriented around a common open area and a common building[1].

A cohousing community is generally designed according to the so called 'social contact design principles'. If a community is designed with these principles in mind the social interactions within the community are thought to be optimally supported. Several studies in cohousing dwellings and buildings show that these aspects like proximity of the dwellings, the position towards other houses, buffer zones between private and general space, surveillance within the community and shared pathways indeed affect social interactions in the community [2-7].

But even though cohousing communities have been designed according to these principles, it is not automatic that dwellers will have an active social life in such a community. The members of the community need to be actively involved in forming the basis for a healthy social interactive community.

Because in cohousing communities there is no condition of management, people are all equally responsible for the organisation for the community. This means that dwellers have to manage their own community and therefore bring formal aspects such as dealing with rules and tasks into their daily lives. It is known that formal interactions are socially more demanding than informal interactions and are more often source for conflicts.

Furthermore the organization of the community drives on consensus. Consensus making is a difficult task, especially when people have different values and goals. Cohousing communities therefore try to attract a homogeneous group of people that have similar values and goals. This generally comes to people that choose to be actively involved in the community and are socially able. For this reason wannabe residents have to take part in a selection procedure to be allowed to join the community. This essential procedure is complicated by the fact that cohousing communities are mostly owned by housing associations which are unwilling to have unrented apartments. This raises the change of unfortunate group settings.

Apart from values and goals the age of the residents in a cohousing community is an important factor. The older people get the more help they need and the less help they can offer to others. In case the average age of the residents gets too high this has a negative effect on the possible interacting activities of the group. Activities sometimes have to be stopped due to the ageing of residents.

In a first conceptual model of interaction [8] the influence of formal interaction, informal interaction, ageing, physical and technical design and personal factors on social interactions have been configured (see figure 1). This model visualises that differences in individual values, goals (and behaviour), technical and physical design influence social interactions in a cohousing community.

It is necessary to know which factors influence social interactions, but this does not directly show how this influence might lead to better wellbeing of individual dwellers.

Social interaction relates to social wellbeing. Social wellbeing is depending on the network of personal relationships and social exchanges that take place[9]. When this network is included in a shared social network with forms of reciprocity and trustworthiness this can be seen as social capital [10, 11]. Social interactions are a structural aspect of social capital. A cognitive aspect of social capital is related to trust and reciprocity of the social network. That places a certain doubt upon the idea that social interactions in it self are predictive variables for

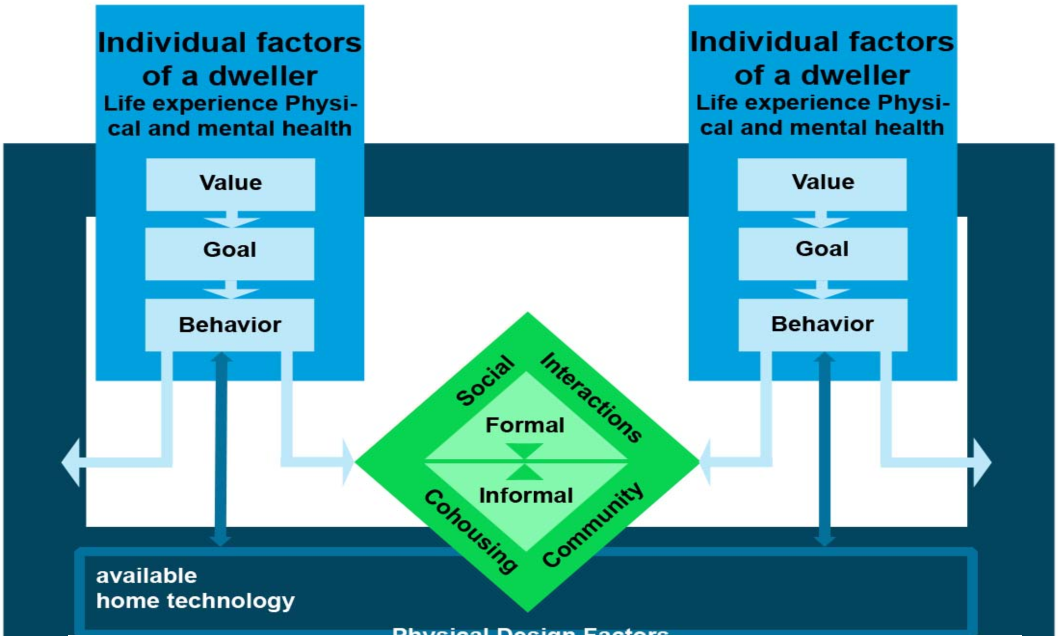

Figure 1: Factors influencing social interactions in a cohousing community for elderly on an individual level [8]

social capital.

In most commur... interpersonal confl... common activitie... regulations [13] and the ongoing design process as a key contributor to conflicts [6]. The more people with interfering values and goals interact with each other, the more likely they have conflicts with each other. Aspects of trust and reciprocity may not be optimal in the case of conflicts within the community.

Figure 1: Factors influencing social interactions in a cohousing community for elderly on an individual level

Furthermore the literature on social capital has pointed out the importance of bonding and bridging contacts for people within a community. Too much in-group contacts (high participation within the group, low trust outside the group) might lead to miniaturization of the group [14]. This means that social interactions within the group cannot provide all contacts for social wellbeing of the individual members.

Based on these insights observing social interactions within a community is just a part of social wellbeing. The quality of the contacts and the contacts outside the community are important as well.

As mentioned before, it has been concluded from literature that the physical design of a cohousing community influences the social interaction in a cohousing community. New developments like the use of atriums, technologies like domotics and ambient intelligence [15] have not been included. The last years there has been a shift from products that react on user input to products that are context-aware, networked and pro-active devices. The enabling technology is available and the focus is shifting towards user oriented challenges: personalization, adaptation and anticipation.

...gent technology. ...) might influence social interactions in cohousing communities as well. According to Friedewald et al [16] an intelligent home should be analyzed from the perspective of supporting families and friends being together and interacting with each other. Basic functions like home automation; communication and socialisation; rest, refreshment and sport; working and living; support the families in achieving their goals.

Not many technology providers have sound knowledge about the social context of the technology they produce [17]. But if technology is aiming to support families (e.g. communities in meeting their goals) it seems important to understand the relation between social interaction and changes in the technical and physical design. If technology would end up isolating people because they were totally depending on the technology in their homes and not in need of any physical help of other people anymore this would be a negative development. On the other hand if it would be possible to influence social wellbeing of dwellers in cohousing communities by technical and physical characteristics a cohousing community might become a more robust sustainable alternative which is suitable for different kinds of dwellers.

Changes in the physical environment can occur when a community is started and the whole community has to learn a new script, or in existing communities when some aspects of the script have been changed. A script is a framework defined by technical objects of action together with the actors and the space they are supposed to act. [18] When the script changes behaviour changes.

This paper presents the relation between changes in technical and physical characteristics and social interactions in a cohousing community.

1.1 Methods

The study was performed in two directions. Firstly information about social interaction and influencing factors was derived from literature. Secondly several student projects were performed that concentrated on the social and physical characteristics of five cohousing communities.

The students performed semi-structured interviews with twelve residents of cohousing communities and collected photographs of the buildings and common areas of five cohousing communities in the northern part of the Netherlands. The residents were chair persons or other members of the boarding group of the community. All dwellers in the communities of this study are originally from the Netherlands. The education of dwellers varies from primary school to university and the professional background from housewives, farmers to higher management. From the interviewed members of the cohousing communities ten out of twelve attended higher education (bachelor and masters degree). Most interviewed consider themselves active residents although having small physical problems.

The communities differ in size and starting dates: community A has 26 apartments and started 15 years ago; community B has 24 apartments and started 12 years ago; community C has 49 apartments and started 5 years ago; community D has 21 apartments and started 22 years ago; community E has 65 apartments and started 8 years ago. A characteristic of all cohousing communities was the use of consensus in decision making.

2 results

The analysis of the physical context of the cohousing communities reveals that in all cohousing communities the design principles for social contact were adopted as all contain common facilities and shared pathways. Furthermore it was established that two of the studied communities are larger than mentioned in literature (49 en 65 apartments). These communities are multi-floored buildings with the use of a central atrium.

The intended role of the atriums was to provide the possibility to have interactions with other residents when the weather conditions are poor. However, the actual use of the atrium in community C does not confer with the intended function in the design, as people avoid social interactions in the atrium. They have tried to improve the use of the atrium with attributes (for fitness), decorations and small plastic plants (see figure 2). The residents mentioned two reasons for their dislike of the atrium. The first reason was that all other residents can overlook the atrium and people wish for more privacy in their social interactions. The second reason was related to the bad climate in the atrium (too hot in the summer and too cold during winter times). The atrium in community E (see figure 3) has the possibility to some privacy due to the use of (big) plants and trees.

Fig 2 and 3. The atriums in community C and in community E

All communities are equipped with a safety system (see figure 4). This system helps the regulation of people entering the building. These systems strife for the situation that nobody can enter the building without the permission of a specific dweller.

The introduction of a safety system in community C resulted in a special meeting with the local firefighters and police on the subject of safety. As a result of this meeting safety was further addressed during a meeting with residents in which formal rules were set about allowing people to enter the building. Chairpersons were made responsible for following the rules and confront dwellers who are less cautious. The number of visitors entering the building has decreased since the introduction of the system.

Fig 4. An example of a safety system in community C

In community A the introduction of the safety system has led to a new informal network according to two dwellers. They can hear the visitors through the intercom by picking up the phone, so they exactly know who is allowed to enter the building and by whom. Because this feature is added to the centrally located parking and the surveillance in the community, privacy is highly at risk. Some dwellers seem to find it very interesting to follow the lives of their neighbors.

In community B the common room (see figure 5) has been improved by addition of some new facilities such as a fire place and a pool table. According tot the chair person this has resulted in a significant increase in the number of residents using the room.

Fig 5.The common room in community B

In one of the older communities (A) new tablecloths were needed because the old ones were outdated. It was arranged in informal consultation that one of the female community members would arrange this. So she bought new cloths. But the community members disliked the new tablecloths very much. They decided during a formal meeting to keep the old ones (see figure 6).

In the oldest community (D) of this case study also some improvements were made on the interior of the common rooms, but this seemed no big issue for the community.

Fig 6. The common room in community A with the old tablecloths

3 Discussion and conclusions

The conducted research is not representative for all residents of the cohousing communities studied, because the respondents were all chair people or board members. Still the results are in line with previous research from Brenton [12] who performed a study on cohousing for elderly in the Netherlands.

New physical and technical design aspects like home technology and the use of atriums have been observed in the newer communities. When new technologies enter the cohousing community this changes the script. Technical objects define a framework of action together with the actors and the space they are supposed to act. [18]. This may lead to expected and unexpected changes in behaviour [19]. In the case of the atriums community gardens have been replaced by a central covered space.

The (dis)use of the atrium in community C was unexpected but the solutions in community E might be interesting to study for this community. The atrium is a new design aspect which has not been considered in cohousing literature. According social contact design principles a buffer zone between private and communal space is an important aspect [6, 7]. A private garden works as a buffer between the communal garden and the private dwellings. In this case the plants in the atrium of community E might work as some sort of buffer zone.

Privacy was also related to the unexpected (dis)use of the intercom in community A. Privacy is related to the individual values and behaviour (see figure 1) but it seems that this can be influenced by the physical design factors. It needs to be studied whether it is true that easy access to personal information is provided the threshold for harming privacy is lowered. However the results in this study seem to confer.

Community C is placed in the Northern part of the Netherlands in a small village with no big criminal records. It is the question whether the implemented safety system is necessary for this community. The alteration in entering the building might in the end result in unwanted social side effects. In literature on social capital the importance of bonding and bridging contacts for people within a community have been pointed out. Too much in-group contacts (high participation within the group, low trust outside the group) might lead to miniaturization of the group. This may lead to unhealthy behaviour [20]. Based on this knowledge it might be suspected that community C could be at risk.

Another notified change in the physical context was the common room in community B. According to the chair person this has led to more use of the room and therefore increasing social interactions. In the research of Willlams [6] the importance of investing in common facilities for social interactions has been regarded. Problems with poor design of common facilities may reduce the extent to which space is used.

Small changes on tablecloths in community A may be a cause for conflicts within the community, while in community D changes don't seem to influence the residents. It would be interesting to know the differences between these groups on aspects as homogeneity, the formal social factors or the cognitive aspects of social capital within these groups.

From the literature and the case studies the following conclusion can be drawn:

- Changes in the technical physical environment influence social interactions in a cohousing community in expected and unexpected ways, though not all changes are effective. Considering social contact design principles might be useful for improving social interactions.
- Changing the environment may lead to direct changes, related to the script of use. But these changes can also be indirect. These are more related to the (dis) likes of the improvement and the formal process itself.
- It is useful to evaluate social interactions in the way they contribute to the social capital of dwellers.

In the next phase of this project the social interactions in a cohousing community will be further investigated through action research; a description of interaction patterns with context information of the interaction will be made. These interaction patterns are deduced from the 5W (who, what, where, when and why) and 1H (How) method [21]. The exact changes in interaction are a step in a better understanding of the relation between technology and social interaction. This may lead to insights which may influence newer developments.

4 Summary

This paper explained the relation between physical and technical design in cohousing communities. Changing technology in the near future might change interactions between dwellers. More knowledge is needed on interaction patterns.

5 acknowledgments

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The Process of Designing with Reused Building Components

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Abstract

Using reclaimed components has significant implications on the “process” of how to design a building as well as its construction. Traditional relationships and design procedures may not be best suited to maximize material reuse and appropriate construction contracts are needed to accommodate component dismantling and reuse. This paper considers the practical implications of component reuse strategies on the process of designing and constructing buildings. How does the design team have to adapt its working methods to maximize the potential for reusing components? What are the contractual and liability issues? What are the implications for the client? The paper highlights the lessons learned from reusing salvaged and reclaimed materials in Canadian construction projects. Using the experience from these projects the paper outlines the differences in process that design teams need to embrace, and some key procedural points that need to be integrated into architectural handbooks of practice.

Keywords:
Reuse, recycling, reclaimed materials, design process

1 INTRODUCTION

The widespread adoption of the green building rating systems such as Leadership in Energy and Environmental Design, or LEED, [1] has had a considerable impact on the industry in North America and has increased interest in reuse and recycling in construction. In addition, difficulties with waste disposal and limitations on land filling have stimulated interest in the potential economic benefits of alternatives. Waste is becoming regarded as a lost resource and a loss of potential profit. Processes that add value to waste materials can lead to significant financial benefits. This has driven considerable interest and research into issues of deconstruction, design for deconstruction, and reuse of components and material recycling. Publications such as “Old to New – Design Guide for Salvaged Materials in New Construction”, published by the Greater Vancouver regional District [2], and “Design for Deconstruction SEDA Guide for Scotland” [3] illustrate the increased interest from local government in North America and Europe for the potential for building material reuse to address waste minimization. In California, the Integrated Waste Management Board published a Technical Manual for Material Choices in Sustainable Construction [4] which outlines the opportunities for reuse in construction, and lists potential components that can be successfully reused. In 2001 the IWMB also published a Deconstruction Training Manual [5] which aims to grow a viable industry and reduce the amount of construction and demolition debris that makes its way into California’s waste stream.

It is generally recognized that the use of recycled materials and the reuse of components in buildings can lead to lower environmental impacts. However, at present, in North America the perceived difficulties inherent in the incorporation of reclaimed materials into new buildings often discourage clients and designers from embracing reuse unless it is for principled rather than financial reasons. Although materials costs can be lower through reuse, it must be recognized that these may be offset by higher labour costs and increased design time, and fees, resulting from more research required by the design team. In addition, there is likely to be greater uncertainty over costs and program as delays can occur if key components cannot be readily sourced or there are delays in the demolition process.

Existing buildings are huge reservoirs of materials and components which can potentially be mined to provide much needed resources. Reuse of many components from old buildings can significantly reduce the life cycle environmental impact of new buildings. It can also create new jobs and business opportunities. There is increasing recognition that use of recycled materials and reused components extracted from an old building can potential lead to a reduction in waste that needs to be disposed of, a reduction in primary resources used and savings in greenhouse gas (GHG) emissions [6].

However, current, standard construction and demolition practices focus on the fastest, easiest and most economical way to get the job done. When this is combined with a lack of clear information and guidance for designers and owners about the implications of specifying reclaimed components and recycled materials, it creates barriers to a more ecologically sound use of resources.

At present, in Canada the perceived difficulties inherent in the incorporation of reclaimed materials into new buildings often discourage clients and designers from embracing reuse unless it is for principled rather than financial reasons. Although materials costs can be lower through reuse, it must be recognized that these may be offset by higher labour costs and increased design time, and fees, resulting from more research required by the design team. In addition, there is likely to be greater uncertainty over costs and program as delays can occur if key components cannot be readily sourced or there are delays in the demolition process. Thus, using reclaimed components has significant implications on the "process" of how to design a building as well as its construction. Traditional relationships and design procedures may not be best suited to maximize material reuse. These issues need to be understood by the design team and client so that appropriate strategies are put into place.

Figure 1: The Mountain Equipment Coop has pioneered component reuse in many of its retail stores. This one located in Ottawa reused many parts of the previous building on site, including the foundations.

2 METHODOLOGY

This paper considers the implications of materials reuse strategies for the process of designing and procuring buildings. The intent is to understand the changes that a design team need to make to the design process to facilitate greater reuse of components in construction and to indicate strategies and recommendations about how to maximize reuse potential. The focus is on how the intention to use salvaged and reclaimed materials affects the design process, and what designers need to know and how they need to adapt their standard processes to fulfill the potential for component reuse.

This paper is based on work carried out to examine the processes used for building component reuse in Canada. The discussion below focuses on key aspects of the design process and how they are affected by component reuse, particularly those aspects that have been identified as potentially varying from standard design processes as outlined in the Canadian Handbook of Practice for Architects [7]. The work is based on a survey that was carried out of the Canadian construction industry. This survey focused on Canadian projects that included significant amounts of component reuse. Key participants in these projects were interviewed or filled out a questionnaire, and this information was analyzed. In addition, a literature review was carried out of international practices for integrating reused components into buildings. A full report of this project is available elsewhere [8]

3 TYPES OF REUSE

Reclaimed and salvaged materials and components (RSMC's) available for reuse can be generally categorized into 4 types:

- On site reused component - which may be whole structures or individual components such as bricks from an old building on a site into a new building.
- Salvaged from other sites – components such as bricks, timber or steel taken from a demolition site and used in another project (usually local), and requiring little reprocessing.
- Reconditioned components – these are components that are taken from a demolished building and require some improvement to be sold again for use in a new location. This may include radiators, doors, staircases, etc.
- Recycled content building products (RCBP's) – these are often readily available building products that include significant amounts of feedstock material that is taken from demolition or other reuse sources. This may include some gypsum boards, steel components, etc.

It is important to keep in mind that using each of these in a building project requires different tasks and strategies at different stages of the design. In addition, current market conditions have an impact on the availability of all these components. Recycled content building products have the least impact on the design process as they are often available directly from manufacturers "off the shelf". Components salvaged from other sites are often the most difficult to integrate as they need to be identified and sourced at the appropriate time in the design process which may be difficult. On site reuse allows the design team to assess what is available and design the new building around the components that are already at the site. Therefore, assessing the potential for different types of reuse, and the sources that are available at the pre-design stage of a project, are essential for future scheduling, resource planning and cost estimating.

4 LESSONS FROM COMPLETED PROJECTS

4.1 Commitment

In the absence of a legal compulsion to reuse and recycle, it is essential that the client or developer is supportive of the principle of component reuse. Projects quickly founder when the client has doubts about this strategy, as inevitably there will be times when the standard product option looks tempting. Also, the client may have to fund the purchase (and thereby securing) of materials and components as they become available throughout the project, which may occur earlier than in a typical project. For this reason it may be helpful to appoint a contractor as part of the design team. This will have implications on the form of contract used, so alternative contractual arrangements need to be discussed with the client, particularly if high levels of salvaged material use are planned.

Expectations for the design may require some tolerance to the duration of the design and construction phases since they will depend entirely on the supply of suitable materials and goods.

The survey of projects that reused components clearly indicated that the decision to focus on RSMC needs to be made early in the design process. Approximately 80% of respondents stated that the decision in their projects was made at the Concept Design stage, with a few making the decision right from the beginning during the Design Team Selection. It appears from evidence of completed projects that if a decision to use RSMC is left until the outline or detailed design stages it is far more likely to have a detrimental effect on costs during construction and schedule while material was being procured. This is often because the design of the building has progressed too far without consideration of what components may be available.

4.2 Costs

Almost half of responses to the survey indicated no impact on design fees, but others did indicate a significant increase in workload for the design team which should be recompensed. It is to be noted that the projects which had higher design fees also had a higher proportion of RSMC and were considered to be pilot or 'test' projects.

There is a strong consensus that material cost (including refurbishment/reprocessing) are decreased by use of RSMC – 95% of responses indicated either minimal or significant savings most likely attributed to the lower costs of used materials even when refurbishment of the component was factored in. Conversely, there is a strong indication that construction labour costs increase, possibly due to additional dismantling and handling costs. Particular cost savings were noted when major components of an old building are reused on the same site in a new structure as they are directly offsetting the purchase of new materials. However, good documentation of the old components is useful to avoid unexpected surprises. It was also noted that transportation costs and the consequent environmental impacts are reduced if components are reused close to their original location, and this is usually the case as most reused components are sourced locally.

Surprisingly, the survey did not identify issues and additional costs related to storage of reused materials. Since purchase may have to occur at a time when materials are available rather than when they are needed on site, there may be longer storage times, but these were not highlighted as a problem, nor were there additional costs identified as linked to this.

4.3 Setting goals

There is inevitably hesitance to set ambitious goals for reuse without previous experience of salvaged materials use. The decision as to what level of use of salvaged material should be determined based on some or all of the following criteria:

- Salvaged materials are most readily and cost effectively obtained in relatively small volumes due to the nature of their supply and the different acquisition processes involved. More efficient use can therefore be achieved in smaller buildings.
- The knowledge and experience of the design team about how and where to located and acquire salvage materials can improve the efficiency and cost effectiveness of the process. So previous experience of the design team and contractor with the use of salvage materials is significant.
- The process of locating and acquiring salvaged materials can be longer and more unpredictable than regular construction materials. Therefore, flexibility in time available during both design and/or construction phases is helpful.
- Opportunities for up to 25% use of salvaged materials can easily be achieved provided that the design uses readily demountable materials such as steel or heavy timber construction since these products represent the largest category of salvaged materials. It is not uncommon to reach 50-75% salvaged material on small to medium sized projects of this nature although these targets may increase the time and effort needed to achieve them.

4.4 Design process

A factor that clearly emerged from the survey was the importance of integration in the way the design team functions as a key reason for utilizing a higher than average amount of RSMC's into their project as well as achieving building energy performance exceeding normal standards. Design teams that employ the Integrated Design Process [9] provide a clear benefit, as this leads to early involvement and buy in from the whole design team. Furthermore, it is important for the design team to be enthusiastic about the reuse/recycle route, and to accept that this may require the team to adapt the normal working practices, and be prepared to take the initiative when it comes to overcoming the unpredictable hurdles that may present themselves. This is clearly linked to remuneration and design fees, but as noted above, if decisions are made early enough the additional design costs need not be substantial.

Previous experience of design consultants with the use of salvaged materials, or willingness to accept the concept and adapt their processes is important. Some firms hire a specific person to source reused materials which may be an opportunity for new specialist roles within design consultancies and for young and enthusiastic employees to learn and benefit from the process. Similarly, the commitment of contractors and sub-contractors to reuse/recycle is recommended as they can assist or be responsible for the sourcing of suitable materials and components. This may require that contractors become involved during the schematic design/design development phases since material acquisition happens much earlier than for typical projects.

Beyond having potential contractual implications, inexperienced or disinterested contractors may have a negative influence on the project team in their use of pressure tactics such as increasing the construction costs due to 'unfamiliar practices' or by not being able to properly locate salvaged/recycled materials. This results in the undermining of the project's intentions by reverting back to new materials and components, albeit with more familiar methods. Thus, the goals of the project need to be clearly explained to, and embraced by, potential contractors before or during the time of tender or contract negotiation.

When reusing buildings and their parts in situ a structural engineer is needed with expertise or past experience in appraising the existing structure and, if necessary, defining work to be undertaken to make the structure reusable, and adapting the existing building for the incorporation of new uses and features (e.g. staircases, lifts, building services plant and distribution). Again however there is the potential issue of an engineer's reluctance in using RSMC by disputing or dismissing the need to properly assess and approve the conditions of potential materials and components. It may be necessary that other building science expertise be sought to also appraise the existing building services, envelope and other features, and to define work to be undertaken to make them reusable, depending on the scope of the reuse.

4.5 Factors deciding what to reuse

When selecting which reused components of a building or recycled materials to use, one starting point that has been used is to base decisions on embodied energy content. It would be appropriate, therefore, to concentrate on reusing and reclaiming goods and materials with high embodied energy as savings will have the greatest potential energy saving impact. This would suggest reuse of metals, plastics, bricks and generally high value processed components. Another approach could be based on the quantity of material available and if used, could theoretically be the total amount diverted from landfills. For this environmentally beneficial scenario, determining the quantity would then be based on the weight or volume of the materials used. In this instance, the focus would be on larger components and concrete which represent the heaviest/bulkiest items to divert.

Unlike traditional projects where designing the structure, mechanical and electrical and other main systems take precedence over final material selection and procurement, when incorporating RSMC the task of sourcing materials is often the driver during the schematic design phase and one of the key influences on the layout, structure and other systems used.

Figure 2: It is often most practical to reuse components or whole structures on the same site. This directly offsets costs and environmental impacts of primary materials.

4.6 Sourcing reused materials and components

Sourcing RSMCs required designers to foster new relationships with organizations they may not traditionally be in touch with. Some demolition contractors, and salvage companies now have sales staff specifically intended to identify and market construction components they have identified as of value to the building industry. These may range from whole buildings, such as prefabricated industrial buildings that can be readily dismantled, to individual components such as beams, stair cases, doors, etc. They often know beforehand when existing buildings are scheduled to be demolished, so establishing contact with them can provide sources for appropriate materials. However, briefing demolition contractors to ensure minimum damage to components scheduled for reuse is sometimes necessary. The UK's National Green Specification [10], for example, calls for demolition contractors to indicate what is to be reclaimed and produce a method statement indicating how the goods will be extracted in good condition, palletized and protected during transportation and storage.

Designers may have to visit local used building materials yards, demolition contractors and salvaged materials suppliers to establish general availability and quality of materials, and to discuss the scope of their project and provide a preliminary list of materials that they are looking for. Larger, or more committed design firms are beginning to develop an expertise in locating salvage components, and may have dedicated staff for this purpose.

Local municipal departments may know when demolitions are likely to occur and can direct design teams to potential sources of materials and components. Furthermore, there are an increasing number of locally based materials exchange schemes often web based that provide access to a range of materials sometimes for free.

Both reconditioned goods and recycled content building products (RCBPs) can generally be sources in the same way as regular materials and components, although additional research may be necessary to identify appropriate suppliers. RCBPs and reconditioned goods are generally easier to acquire due to their availability, and can be incorporated and procured in a similar way to new material up to and during the schematic design phase. For reconditioned goods, during schematic design, responsibility for component acquisition would still need to be allocated as there may be additional tasks associated with locating appropriate supplies. It needs to be established who will source the particular components? Will the design team specify the performance requirements and pass this function on to the contractor with a general requirement that reconditioned components should be used, or will the design team locate the specific component? Most of the survey respondents suggested that in existing projects building components were generally defined by a performance specification and that the contractor was responsible to source the components. This would therefore require that the specification, in addition to a performance statement similar to goods made with new materials, indicate either the amount of recycled content required within the material or that the component be reconditioned.

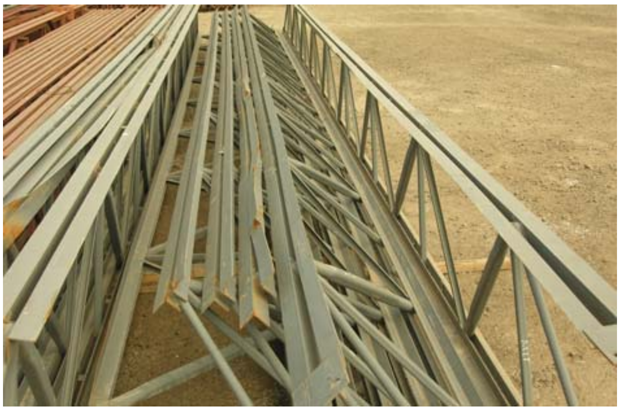

Figure 3: Open web steel joists can often be dismantled for reuse, but the new structure needs to be designed around the available spans.

If the intention is to reuse all or part of an existing building in situ, the search for available existing buildings for reuse in their entirety will need to commence at the pre design stage of the project. Once an existing structure is identified, a full survey of the building to be reused is needed and if possible, original drawings and specifications should be located to assist with identifying potential material re-use opportunities and dismantling efforts.

4.7 Construction process

When reusing buildings and their parts in situ, preferably a deconstruction specialist should be hired if possible, or a contractor with an interest in deconstruction, in order to dismantle the salvaged materials designated for re-use. Some projects in Canada have used not-for-profit / youth programs / government job skills training program as sources for lowering the cost of dismantling and re-conditioning as well as providing economic opportunities for the less-fortunate.

The design team needs to establish procedures for grading salvaged components to ensure they meet functional requirements and regulatory standards. This may require visual inspection, structural or other testing, and possible refurbishment.

5 Conclusion

Certain key factors emerge from the pioneering projects that focus on reuse. These include:

- It is important to have commitment of the entire design team at the early stage of the process.
- Projects need clear goals with commitment of all the design team and client.
- The Integrated Design Process facilitates a great likelihood of successfully using RSMCs
- Sourcing RSMCs required designers to foster new relationships with organizations they may not traditionally be in touch with.
- Responsibility for identifying RSMCs needs to be clearly established - who will source the particular components?
- Procedures for grading salvaged components need to be established and any regulatory issues identified.
- Cost savings are possible in material costs, but some of these are offset by additional labour costs.
- There can be additional design costs. This can be due to redesign to suit when sourcing reused components.
- Projects with the highest savings usually focused on reuse of the existing building already on site.

Designers need to recognize that there are some significant differences to the design process if reuse of construction components is a goal of a project. Reused components have different patterns of availability which need to be accommodated. Also, the limited range of components requires the design team to be more flexible and to develop the building design around the available reused components rather than the traditional process of designing the main features of the building and then identifying the components that will meet the required specifications. This means that ideally the specific reused components need to be identified at an early stage in the design process, perhaps when traditionally a contractor may not yet be involved.

The standard design stages as outlined in the Canadian Handbook of Practice for Architects (and other similar manuals in other countries) will need to be adapted with new tasks included that focus on what needs to be achieved and at which stages, to facilitate successful component reuse. It is hoped that the next stage of this work will develop a manual of tasks to help design teams that wish to design with reused components.

6 acknowledgments

The paper is based on work funded by Natural Resources Canada and the Canadian Institute for Steel Construction and it looked at the potential for reuse of construction components.

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Supply Driven Architecture (SDA)

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Abstract
Waste problems in building industry are subject for discussions in politics as well as in architecture and science. Solutions are searched for in the field of sustainable materials and in reuse of buildings and/or building elements. In this context “design for disassembly” [1] is an important issue. The disadvantage of restricting the reuse of building components to buildings which are designed with this purpose in mind, is that a lot of opportunities of reuse are not utilized. Although most of the building stock is not designed for disassembly, practice has proven that for many objects disconnection and reuse of building components is interesting from a technical as well as from an economic standpoint.

Keywords
reuse, building components, databases, sustainability, methodology

1. INTRODUCTION

At this moment architects have extensive freedom to use materials and components and this freedom will degrease in the near future when they will have to take the supply side of reusable materials into account. The design of demountable building systems is therefore an issue, which has the attention of many researchers. New buildings, designed with demountability as a starting point are built these days, but it will take many years till the environmental profit will pay back. And then it will concern only a small part of the building stock. The larger part will be constructed in traditional ways.

Technology can be applied to realize demountability, but technology can also be applied for deconstruction of traditional buildings in a way that parts are re-usable.

In this context we can distinguish three kinds of technology:

- product technology
- manufacturing technology, and
- design technology.

For Supply Drive Design we will need all three kinds of technology.

Product technology refers to the new building to design. Key question is how we can realize the necessary functions in the new building with re-usable components.

The challenge is to meet modern building standards regarding safety, energy use, comfort and esthetics.

Manufacturing technology refers mainly to the way how interconnect the re-usable components in the new building, but also how to upgrade and transport them.

Design technology is the key technology needed for successful SDA. The challenges of Supply Driven Architecture are hidden in the constraints connected to the specific properties of the available components. An architectural design will become a compromise between the goals of the architect and the design space offered by the available components.

Crucial is the availability of information from the supply side. Components should be extremely well presented and documented.

The objective of research activities in the context of Supply Driven Architecture is to build a body of knowledge about the feasibility and consequences of SDA, as well as finding out what methodological consequences it could imply for the profession of architecture.

Questions to be answered are:

1. Could the supply side be able to offer enough options for the architect to be interesting? (What are the experiences with existing databases like the Reststoffenbeurs [2])?

2. Could software help, in what way, to offer opportunities from the database to find the optimal components for the architects assignment?
3. Could the database inspire the architect for new architecture or will SDA decrease the creativity?
4. Is the quality control problem solvable, as it is in automotive where databases for re-usable components are widely accepted?

2. STATE OF THE ART

There is a lot of experience with the re-use of materials and components in architecture, but this experience is often related to local projects and to a one-to-one relation between source building and target building. (Gorgolewski 2008) [3]. Policy has been developed for encouraging the re-use of materials and components, by also these initiatives are quite local.

Of course the success of Supply Driven Architecture is dependant on the stock of buildings which is at the end of their economical and/or cultural life time.

The Dutch company Bouwcarrousel B.V provides on her website [4] many demolition projects in which materials are reclaimed. Generally spoken there is a lot of supply. Examples can be found in the report “Building Deconstruction and Material Reuse in Washington, D.C., (U.S. Environmental Protection Agency, December, 1999) [5].

It explains that the potential growth and sustainability of a building deconstruction and material reuse program in Washington, D.C. requires an adequate supply of buildings suitable for deconstruction. In order to begin to characterize the existing "stock" of potential deconstruction sites, the National Association of Home Builders Research Center ("Research Center") completed an initial inventory and assessment of 236 condemned residential structures in the District of Columbia. The Research Center completed drive-by, visual inspections of 86 of the 236 condemned properties identified by the DCRA. The visual inspections noted: building type, general construction type, overall condition, property status (e.g., abandoned, effectively cordoned, under renovation, for sale), neighborhood context, and whether a detailed assessment would be appropriate. Based on the inspection of condemned properties, the Research Center defined four categories of residential buildings, as described below, each with attributes that suggest the potential for cost-effective deconstruction. The Research Center then chose four different types of structures for detailed assessments. These assessments provide an indication of the type and quantity of materials available from residential buildings.

• *High-rise multi-family buildings*. These large apartment buildings potentially contain many interior features that could be salvaged and reused (appliances, cabinets, fixtures, etc.). These buildings are usually made of structural concrete and steel, so complete deconstruction is generally not a feasible option. However, the structural materials may be good candidates for recycling. A detailed assessment of one building in the Arthur Capper public housing complex identified cabinets, stainless steel sinks, garbage disposals and metal framed windows suitable for salvage, as well as copper piping and aluminum baseboard heating units that could be removed and sold for scrap.

• *Low-rise multi-family buildings.* These buildings offer significant potential for the deconstruction of both interior and exterior materials. In general, the low-rise multi-family buildings in D.C. are made using brick and block construction with wooden roof assemblies. Many interior elements (e.g., appliances, cabinets) can be salvaged from the low-rise buildings. A detailed assessment of one building in the Kentucky Courts housing complex identified wooden roof trusses with plywood sheathing, recently updated kitchen cabinetry, stainless steel sinks, garbage disposals, and metal framed windows. As with the high-rise example, this building also contained copper tubing and aluminum heating units with potential scrap value. A second detailed assessment, of a three-unit building in the Frederick Douglass housing complex, found a significant amount of salvageable material including framing lumber, brick double glazed windows, and over 1,000 square feet of oak strip hardwood flooring, as well as a recently replaced gas boiler and water heater. There are approximately 107 buildings of similar type in the Frederick Douglass complex, 83 of which are also reported to have exterior natural wood siding suitable for salvage.

• *Rowhouses.* Rowhouses offer multiple deconstruction opportunities. Exterior construction offers salvageable brick, roofing and architectural details. Rowhouse interiors can provide valuable wood materials. A detailed assessment of a rowhouse in Northwest D.C. identified framing lumber, hardwood flooring, oak stair cases, plywood sub-flooring and roof sheathing, and a recently replaced gas water heater and furnace. The exterior of this structure features Roman brick, stone lentils and slate roofing. It should be noted that adjoining rowhouses, particularly those that are not end units, may have a structural interdependence that would need to be considered prior to deconstruction.

• *Single-family dwellings.* Wood-framed single-family dwellings offer significant potential for deconstruction, since it may be possible to salvage nearly the entire structure. The same types of materials found in low-rise multi-family buildings can be expected to be found in single-family homes (i.e., wooden framing, roofing materials, flooring, windows, cabinets, appliances, etc.). However, it should be noted that wood-framed single-family homes represent a relatively small percentage of the D.C. residential housing stock. This is one of the few examples of inventories made of housing stock , especially with re-use of components and materials in mind.

Mark Gorgolewski (2008) carried out investigations regarding utility buildings. In this cases components were directly applied in a new building in the same area. Although this approach is different from that of SDA we still can learn from his findings.

His conclusions were:

- such a project needs more time, because design can only be detailed after information about saved components are available
- the design costs are significantly higher, because of dealing with limitations
- design and construction process changes as a result of complexity

- developing a design around available components provides also opportunities and a foothold
- specialists might be necessary to asses special materials and components. Budget should be planned
- SDA requires a large amount of flexibility from design team
- reuse in easier when application is about the same as the original one
- light weight open structures are vulnerable and therefore more difficult to re-use tha, wooden beams and hot rolled profiles
- bolted connections are preferred. Welded connections easily cause damage
- contractors need special education for this kind of projects
- the client should be motivated for the project.

In the report of the National Association of Home Builders Research Center several factors are mentioned that could limit potential demand, such as:

- a lack of public and/or contractor awareness about the availability of salvaged materials
- a lack of an awareness of the significant price difference between new materials and salvaged materials
- the "hit or miss" problem of not being able to find a salvaged material when needed, or enough of a particular salvaged material to complete the project
- a lack of awareness about the environmental benefits of using salvaged materials, and perceptions that salvaged materials are inferior.

In addition, six demands can be distinguished for successful Supply Driven Architecture.

1. Expertise should be available regarding the assessment of buildings with respect to reusable elements.
2. Expertise should be available with respect to the controlled demolishment of buildings to save valuable components.
3. Facilities should be available to assess and certify the components related to specific applications
4. Facilities should be available to store components waiting for an application.
5. The stock of components should be made accessible for architects.
6. Incentives should be offered to architects who apply reusable materials, with the environmental profits as an argument.

In the next paragraph some information will be provided about experience from existing projects.

Expertise regarding assessment of buildings to be demolished

Deconstruction is widely regarded as a relatively low-skill activity. While this is true for the bulk of work conducted at a deconstruction site, the overall deconstruction process must be managed with skill and expertise. The most important skills required for the successful implementation of deconstruction projects are the ability to assess a structure for its deconstruction potential, to plan the optimal sequence of tasks, and to train and direct laborers in proper deconstruction techniques to ensure that salvaged materials retain their maximum value. Individuals currently active in related construction trades (i.e., with an existing understanding of building and materials concepts) will likely make a fairly easy transition to the deconstruction arena. The availability of the necessary expertise should naturally increase in response to the growth of a market for salvaged materials.

Expertise might be built up is special types of building.

Haico van Nuenen (2000) [6] studied the potential of post war system buildings in the Netherlands and found out that important environmental savings would be feasible. Deconstruction of the concrete elements turns out to be easy because of the poor quality of the applied cement.

Assembly of these elements in a new building is realized with newly designed interfaces, which are hidden behind a second wall, having just an esthetic function. According to Van Nuenen the environmental savings of re-use of components are considerable. He expects savings at least 35% for the first re-use and 60% for repeated re-use. For recycling on material level (granulates) are only 5%.

In the SenterNovem Report (No) Flat Future [7] it is concluded that of post war high rise apartment buildings about 50% of components could be re-used, but that also obsolete office furniture and furnishings from the area of Rotterdam could provide material solutions for producing 'new' apartment buildings. For the writers of the report, Bouwcarroussel and 2012 architects, re-use does not have to take place in the same functions. E.g. systems ceilings could be used for sound insulation purposes and kitchen sinks as roof covering.

Expertise regarding controlled demolishment

A Dutch company, specialized in controlled demolishment is Bouwcarroussel. Expertise was developed by this company itself, but there are no specialized educational programmes in the Netherlands.

In Washington DC the district supports general job training programs that often have construction-related components. For example, in 1999 the Job Training Partnership Act, sponsored by the D.C. Department of Employment Services, provided counseling, training referrals and monetary assistance to approximately 1,000 people; approximately 150 people received construction-related apprenticeship training.

These initiatives may set a trend in building education in general. It is more and more recognized that controlled demolition is a profession with at least the complexity of building construction.

Modern technology is needed to assess constructions and to separate components from each other without causing damage to the components.

An important point is that architects should be involved in deciding about saving components. Who could better represent the needs of architects than architects.

2012 architects introduced the word “harvesting” (oogsten) to indicate a new activity in which a circle of a certain amount of kilometers is investigated for usable materials, keeping themselves open for inspiration.

Assessment and certification of components

Contaminants such as oil, fertilizer, lead and asbestos inside a building can affect the quality and value of materials. There may also be additional liability issues associated with deconstructing contaminated materials. Assessment of these issues is an expertise which is crucial for the success of SDA.

The main problem however is the assessment of the mechanical properties of the components and the standing of surety. For this problem modern technology could bring important solutions.

First of all 3D laser scanning could produce 3D files, which could be the input for FEM (Finite Elements Method) calculations of strength and rigidity.

Ultrasound and roentgen analysis could detect impurities in the materials and lab-on-chip technology could take care of chemical analysis.

For successful application of these technologies in SDA the equipment should become more mobile and user friendly.

Procedures for assessing the specifications of components should be certified in order to protect architects applying reusable components against claims.

2012 Architects

Storage of components

According to Washington DC report one of the largest barriers to salvaging building materials is the lack of convenient and affordable storage space. It reports, for example, that project managers could not find any affordable storage space in the district. Instead, they had to rent a truck to transport salvaged bricks and other items to a farm 20 miles outside of D.C., where they were stored until they could be used at the demonstration house. In addition, some materials had to be stored outdoors, causing damage that precluded their future reuse. A previous non-profit distributor of salvaged materials, Movement and Acquisition of Gifts in Kind (MAGIK), also could not afford the high cost of warehouse space in D.C. This was one of the reasons that MAGIK eventually went out of business.

The costs of storage of salvaged materials are related to three parameters:

- Price of storage space
- Period of storage
- Transport costs

The price of storage space is strongly dependent of the distance from economic centers, as well as transport costs. These parameters neutralize each other, so storage period is the most important parameter to be influenced.

The question is how to influence the waiting time for a user. This waiting time is dependant of:

- the need for the specific kind of components
- the possibility to find the component

For the first aspect marketing information about the need of components has to be available before deciding storing the components.

With respect to the second point we come to the main issue of this paper, the input of the information in the design process. In this respect it is interesting to investigate to what extent architects could be influenced to use re-used materials.

At this moment, in the Netherlands there are more then ten warehouses for re-usable building components. This amount is expected to grow in the future.

Accessibility for architects

Supply driven design is nothing new for architects. Since Vitruvius architects are dependant on the supply of materials. Building tradition started with using materials from the direct environment applying wood, rock and loam. The second step was upgrading those materials by forming it to building components, or even baking clay to bricks.

As far as possible, materials were collected from elsewhere, like marble from the mountains to Rome. The collection of building materials from elsewhere was restricted to rich and mighty people.

Nowadays it is quite usual that a building is composed of materials collected all over the world. Aluminum comes from South America, glass from China and wood from Canada.

Due to this globalization of building materials and components industry, architects are spoiled. The availability of options is nearly unlimited and architects hardly have to cope with limitations of supply anymore. However this has resulted is considerable environmental pollution.

An SDA approach would imply returning to the old situation of limited supply, dependant of proximity. However, times have changed. The limitations will, different than in the past, not be in the amount of material options, but much more in the physical condition of components.

Is this a limitation or a challenge? Could the limited availability of components be a source of inspiration for architects rather than a constraint?

It is well known that some architects like to start from clear constrains such as an existing building structure. Designing a building with a database of re-usable materials as a starting point could possibly be appreciated by many architects.

An initiative by 2012 architects years ago came to early. At this moment it could be about time to start an internet community again.

Incentives

Many example of providing incentives to supply driven architecture initiatives can be found in the United States of America. *(Building Deconstruction and Material Reuse in Washington, D.C., Urban and Economic Development Division U.S. Environmental Protection Agency,*

December 1999)

For example, in the district of Columbia Enterprise Zones (EZ), tax benefits are available for initiatives in this field.

Even lotteries were organized to come with initiatives for renovation projects based on reused building components.

One of the important arguments of the government is the positive influence on employment. Supply Driven Architecture means investment using local labor rather than in new materials and components which are often produced elsewhere.

The best incentive would be a system like CO2 rights on a project level. Direct translation of CO2 earnings to building costs would stimulate green building activities enormously.

3. SDA BASED METHODOLOGY

An interesting initiative with respect to SDA is the "Old to New" design guide by the Buildsmart organization in Vancouver, Canada (2002) [8]. The book provides a lot of information to designers, which is specific for dealing with salvaged materials, also about the availability of many material categories.

The book is based on many case studies of projects in which recycled materials and components played an important role.

The authors did not come to conclusions with respect to the overall design methodology, but mainly focused on the material acquisition process.

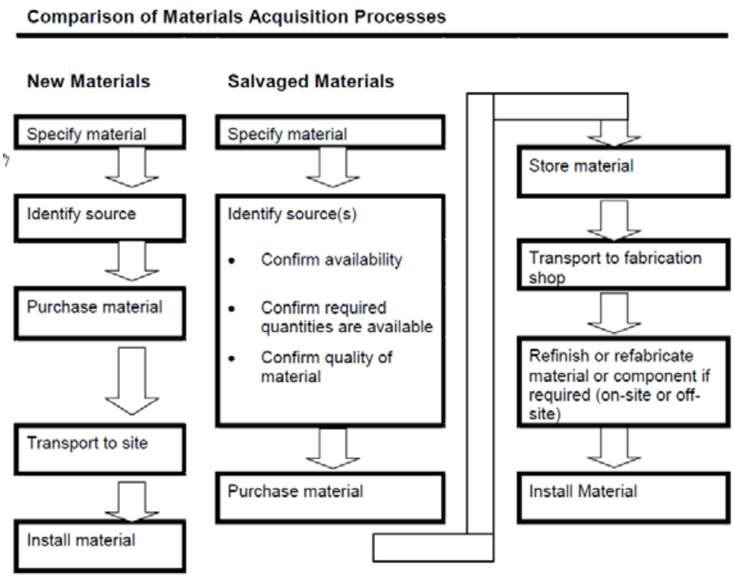

Figure 1. Comparison of Material Acquisition Processes (Buildsmart 2002)

We see that the materials acquisition process is much more complicated applying salvaged material in comparison with new materials. It is not just about identifying sources, but also confirmation of availability conform required quantities and quality is extremely important. Furthermore, it is not just about installing the materials. Storing and transporting of salvaged materials induce specific problems. Especially refinishing and/or even re-fabrication might be necessary. For a specific building (Liu Centre, Vancouver) the design Guide (2002) presents a cost analyses.

Although the additional costs of modification and consultancy are incorporated, we see in this example that there is a cost reduction, compared with virgin materials of ca. 50%. There are no figures about environmental profit available, but it is obvious that these profits are considerable.

Table 1. Cost analysis (BUILDSMART 2002)

4. SDA MOTIVATIONS

However, the whole approach of the Old to New Design Guide has a smaller scope of SDA than meant in this paper. The starting point of the guide is of a defensive nature. The goals are restricted to environmental and financial profits. However, the authors pass over one aspect of SDA being the potential architectural and cultural gains. We still live in a society in which new is better then old unless it refers to recognized cultural values. However, several architects and artists who worked with salvaged materials have become world famous.

We can distinguish four kinds of motivations in SDA.

1. Artistic motivations
2. Environmental, idealistic motivations
3. Economic motivations
4. Architectural motivations.

For each category an example is presented.

Figure 2: reused tiles by Hundertwasser [9]

One of the most famous SDA examples are provided by Friedrichsreich Hundertwasser who applied broken tiles, but also old lampposts in his architecture, which is, generally spoken regarded rather as art then as architecture.

Cost Comparison of Salvaged and New Materials

	Salvaged Materials		New Material	Difference
Material				
Glulam Beams	-$200			
Testing* / certification / storage	$1,750			
Refinishing	$4,500			
Modification of beams and steel connectors	$3,300			
Total		$9,350	$24,500	$15,150
T & G wood decking	$7,150			
Refinishing	$2,975			
Freight / contractor o/h	$2,350			
Total		$12,475	$24,000	$11,525
Concrete Pavers	$1,000			
Shipping	$400			
Total		$1,400	$2,700	$1,300
Total Salvaged Material Cost		**$23,225**		
Cost of Comparable New Material			**$51,200**	
Cost Savings to Owner				**$27,975**
Additional Consultant Costs				
Architect		$5,650		
Total Project Savings				**$27,975**

* Testing for adhesive strength, by Levelton Engineering.

Figure 3: Family Thrift Store, Missouri, USA [10]

environmental, idealistic motivations played a key role is the Familly Thrift Store on Fitzerald Avenue in Gerald, Missouri. It can be characterized as home made architecture and a "Ramshackle masterpiece (Michael R. Allen 2009). An important material source was a Roman Catholic Church.

Figure 4. Glass House of window frames in Christiania, Denmark [11]

An interesting example of the social acceptability of architecture with reused materials is the project Christiania in Copenhagen, which was regarded as "an important corrective to a consumer society run amok".

Sometimes idealism has less to do with SDA then the wish to create impressive buildings using components of impressing buildings from the past. An example of this is Kerckebosch in Zeist, which is now a hotel of the Bilderberg group. French castles were the source.

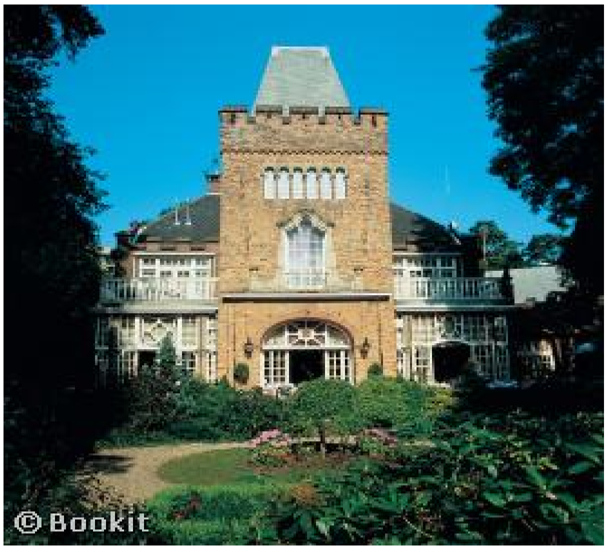

Figure 5. Hotel Kerckebosch in Zeist [12]

But there are also pure economic motivations for SDA.

An example is the building of the Mountain Equipment Co-op in Ottawa Canada (Gorgolewski 2008). In this utility building many materials from an existing building on-site as well as from other locations are applied. Of course, many investments were necessary to meet the modern standards which resulted in a building price of about the same as new buildings. Without environmental incentives it is not easy to earn money with reuse of materials due to higher design and handling costs.

Figure 6. Mountain Equipment Co-op in Ottawa Canada (Gorgolewski 2008).

This example shows that SDA does not necessarily lead to shackle architecture like the Family Thrift Store.

The Powers-Hanson House is an 850 s.f. strawbale home built from natural and reclaimed materials in Teton Valley, Idaho. The home features passive solar heating, earthen floors, and natural plasters.

Figure 6. Powers-Hanson House [13]
(www.naturaldwellings.com)

Inspiring is the work of an Austin (Texas, USA) based builder “Reclaimed Space”, who not only has taken reused materials as a starting point, but also move-ability.

Figure 7. Project in www.reclaimedspace.com [14]

One of the Dutch projects in this context is the Villa Welpelo by 2012 architects. For the support construction of this villa an obsolete paternoster was applied. The cladding is made of obsolete cable-reels from a cable-factory in the neighborhood. The wood was Platonized for durability reasons.

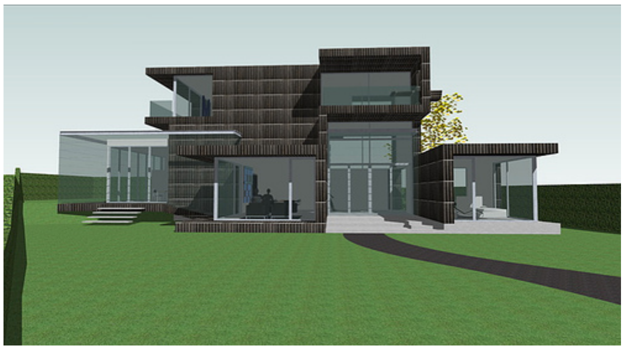

Figure 8. Villa Welpelo by 2012 architects [15]

5. DISCUSSION

SDA is can be regarded as a new trend in architecture which will become important in the decades to come.

However, the success is dependant of four conditions:

1. Financial incentives for reusing materials
2. A positive image of buildings created with reused materials, as a result of high quality design
3. A well structured infrastructure for deconstruction of buildings, communication about useful components as well as storage and distribution.
4. Education of architects who are able to cope with the specific problems of reusing building components.

Research will be initiated at the University of Twente to build up a body of knowledge on these issues.

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Conservation of Resources by Designing a Meccano for Temporary constructions

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Abstract
Reusing building components is an effective way of conserving embodied resources, materials as well as energy, in a life cycle perspective. However this requires innovative design, which anticipates an eventual demolition and provides versatile and adaptable constructions. This paper shows how constructions and their components can be designed with the necessary reuse qualities, by using a minimum number of different components. To monitor the environmental load of such Meccano-like designs, an assessment method that focuses on the conservation of embodied resources is detailed in this paper. The environmental benefits are discussed through the design of temporary constructions.

Keywords:
reuse; building components, life cycle, environmental load assessment, Meccano

1 INTRODUCTION

The human built environment surrounds us: we live and work within it. A growing human production and the rise of a non-agricultural economy in the last centuries, coupled with the expanded use of fossil energy and dumping of tons of waste material, have dramatically increased the environmental impact of buildings and constructions on a local and global scale.

The increasing importance of environmental protection and the awareness of impacts of products manufactured and consumed have intensified the interest in the development of methods and tools to comprehend and reduce these impacts. Life cycle assessment (LCA) is a technique, still in stage of development, for assessing impacts associated with a product or service in a life cycle perspective. Requirements regarding environmental impact may be expressed in terms of use of materials, use of energy, use of water, emission of substances – including hazardous and toxic emissions – use of land and biodiversity. [1]

Reijnders and van Roecke have made a rough division of assessment tools in two distinctive classes: qualitative tools based on scores and criteria, and quantitative tools using a life cycle model with quantitative input and output data on flows of matter and energy [2]. The latter class of tools has only been available on the open market for the last 10-15 years and has therefore not been used as extensively as the former. With a growing understanding of cities and the built environment as systems metabolising matter and energy, the use of quantitative tools are expected to increase [3].

2 TOWARDS AN INTEGRATIVE LIFE CYCLE MODEL OF THE BUILT ENVIRONMENT

In the built environment (excluding urbanism) three life cycles can be discerned: the cycle of the **building**, the cycle of its **components** and the cycle of the **materials** used to manufacture the components. Even though these three cycles become one during the use of the building, this is not the case before construction and after dismantling. For a total picture of the material and energy flow (and their side effects) it is thus important to take into account all cycles. Since in most Western buildings the energy consumption during service is undeniably the biggest input, the 'splitting up of cycles' is often neglected by most quantitative assessment tools [4]. This also explains why lowering the operation energy has granted the main focus of researchers and policy makers. Passive energy, proper insulation, natural ventilation and low consuming lighting and heating are highly promoted through Western and Northern Europe. Thanks to sound technology and environmentally friendly design principles the energy consumption of future buildings should drop.

Studies on modern low energy dwellings have shown that the energy needed for production can account for 40-60% of the total energy use [5]. This proofs that the consumption of energy and other resources before and after use of the modern building is not negligible anymore in the energy consumption assessment.

Since an important goal of the building sector is to produce constructions with a low environmental impact, not only their operating energy, but also the embodied resources (EX) of their components, i.e. the amount of resources (X) acquired for all processes from extraction of raw materials up to the manufactory of building material and/or prefabricated construction elements, should be minimised. To achieve this goal it is important to take into account a life cycle model, in which the three levels – construction, components and material – are integrated.

2.1 Flows of resources

After the use of a construction various management choices which affect the total energy input and material flow are suggested. Typically seven different 'paths' can be followed [6, 7]. In two of them the building remains standing (paths VI and VII); in the other five cases the building is partially or totally disassembled or demolished. After sorting, building components and/or materials are taken out of the cycle (paths I and II) or a second life is offered (paths III, IV and V). All seven possibilities are defined in the next paragraphs.

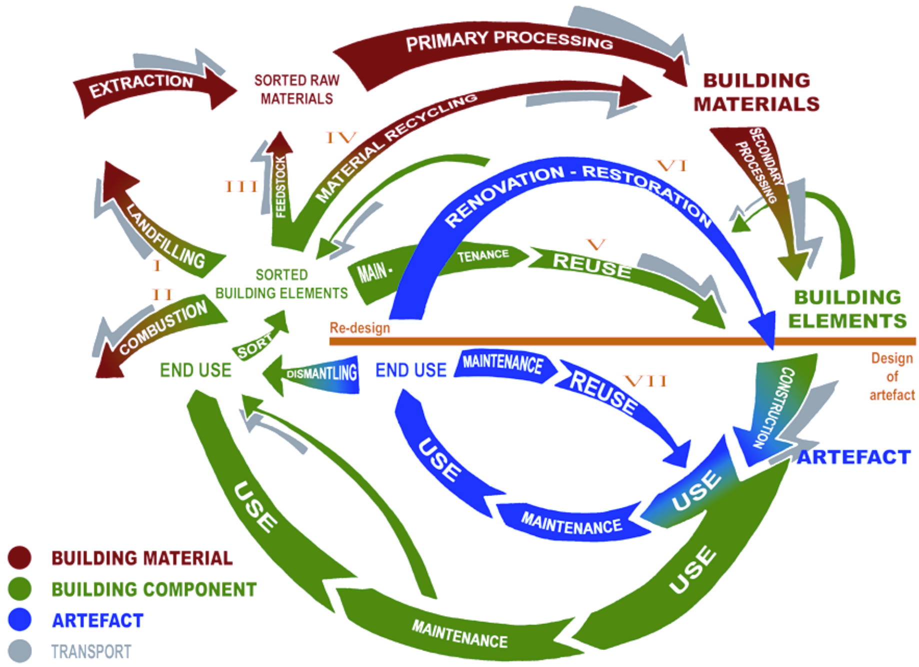

Figure 1: integrative life cycle model of the built environment.

Path I: Land filling. All or a part of the sorted components are disposed of by burying it. No saving on the total energy input can be considered. Moreover energy has to be taken into account to transport the waste to the disposal site and to bury it. Most common side effects of inorganic components are erosion and pollution of air, water and soil. In contrast, the disposal of some biodegradable construction elements or materials can nourish the site instead of damaging it. McDonough and Braungart [8] promote natural disintegration of waste through use of a design approach wherein biodegradable components and recyclable components can easily be separated. In the long run the assimilation of biodegradable materials by nature could offer new organic materials for production.

Path II: Combustion. All or a part of the sorted components are burned. Material is permanently taken out of the cycle(s) in the form of small particles and GHG emissions. Thanks to the exothermic process energy can be recovered in form of heating or electricity (E_{RECOV}).

Path III: Feedstock recycling. This type of recycling refers to a process where the sorted components are reprocessed into raw materials or 'feedstock' to make building material(s). E.g. a glass bottle can be recycled into aggregate. Still a high amount of energy is needed to reintroduce the material into the cycle. The emission of greenhouse gases has to be considered.

Path IV: Material recycling. During this process separated components are directly reprocessed into building material(s). E.g. a glass bottle can be recycled as glass. Still a high amount of energy is needed to reintroduce the material into the cycle. The emission of greenhouse gases has to be considered.

Path V: Reuse of components. Here, sorted elements are, after a maintenance procedure, 'recycled' into the same components for similar or other purposes. E.g. a glass bottle can be reused as a glass bottle after washing it. If maintenance procedures are too labour-intensive and/or too costly, another path is recommended.

Path VI: Renovation or restoration of the building. Although the building can be partially demolished or dismantled, part(s) of it remains. External and/or internal additions to the existing building are performed through implementation of new building elements. The reinstated artefact can fulfil the same or another function. Since most buildings are not designed to be easily restored, it is often a costly operation involving necessary expertise.

Path VII: Reuse of the building. The building stays the same. Only minor maintenance is needed to extend the use of it. The reinstated building can fulfil the same or another function. Spaces which have a versatile or flexible character facilitate functional changes.

The seven flows are illustrated in the model shown in Figure 1. It gives a life cycle representation of the different levels of the built environment - excluding urbanism - and the complex relations between them.

2.2 Transport

Although frequently underestimated, transport of matter and building components in the stages before and after use of the construction can embrace an important input in the total energy of the cycle(s). In Figure 1 transport is illustrated as grey arrows shadowing the related processes. Transport energy is difficult to calculate since it depends of a great number of parameters, such as the distance to be carried out, the mode of transport (lorry, train, ship) and the capacity and consumption of the means of transport.

3 4DIMENSIONAL DESIGN

Reuse of buildings, components and materials plays an important role to prevent and reduce demolition waste and energy consumption during the production of building materials and elements. However, reuse at superior levels is only possible when it is taken into account during the (re-)design phase of the construction.

4Dimensional design (4D) refers to an attitude of the designer, using his/her talent and horizontal knowledge to provide an artefact with a sustainable character, according to a life-cycle perspective. This has to be done by integrating the fourth dimension, i.e. time, in the first stages of conception. Time is not only related to the wear and tear of the artefact, but also to changing and evolving circumstances which will affect it. In this sense the artefact and its components must have the potential to adapt to unexpected changes. Consequently, a 4D designer considers an artefact as a materialised answer to a process of changing events. Even when (s)he can not predict with great certainty how governing circumstances will evolve, the artefact may not be a static result of a pre-programmed end state. [9, 10]

3.1 Hendrickx-Vanwalleghem design approach

Architects H. Hendrickx and H. Vanwalleghem have developed a design approach to stimulate reuse in the built environment. The Hendrickx-Vanwalleghem design approach (H-V design approach) includes a 4D view on the built environment [11]. It encloses guidelines to design multiple construction systems, all compatible to each other, by which a variety of adaptable and reusable construction elements can be composed. Each construction system is made of a minimum number of basic elements and a set of combination rules. They allow the conversion of each artefact to a different configuration, by means of adding, removing or transforming the basic elements it is made of. It offers a high potential of recycling and direct reuse. The outcome can be compared with the Meccano building set, which, in this view, encloses all materials and techniques, and is applicable to all scales. [7, 10]

4 AIM OF THE STUDY

The aim of this study is to evaluate the environmental benefits of the H-V design approach. This is done by calculating the environmental load of a building kit for temporary constructions, such as multi-use infrastructure for peace supporting operations. The paper will focus on the potential savings on embodied energy and natural resources of reusable components and constructions.

5 ASSESSMENT METHOD

5.1 Calculation of flows

According to Fay and Treloar, an easy way to assess the environmental load of a system is to calculate the amount of energy and resources needed during the systems life(s) or during a part of it [12]. This technique is popular in the building and construction industry (B/C) since buildings and constructions are often energy and material intensive. With Kyoto targets necessitating the quantification of greenhouse gas emissions at the national level, it seems more and more likely that life cycle energy analyses (LCEA) will increase in use [12]. In this technique the focus lies on the inflow of the environment (i.e. resources) and not on the outflow, thus excluding the impacts of emissions on soil, water and air.

Operational energy

The total energy input during use of a construction (E_{USE}) is usually defined in the following way:

$$E_{USE} = \int_{0}^{ESL} OE(t)\,dt \quad (1)$$

With:

- OE : total operational energy (including thermal and non-thermal) for a given time span (e.g. one year)
- ESL : estimated service lifespan of studied construction
- t : time, usually in years; for t = 0: OE is considered nil

In this definition of E_{USE} a varying performance of the construction (e.g. due to the degradation of thermal insulation) is taken into account.

Life cycle energy

Life cycle energy of a construction (LCE) comprises energy consumed before, during and after the construction is used. Taking a detailed life cycle model of the built environment (see Figure 1) into consideration, LCE of a construction can be formulated in the following way:

$$LCE = EE + \left(E_{USE} + E_{MT}\right) + \left(E_{DIS} + E_{SORT} + E_{TR,SORT} + E_{EoL}\right) \quad (2)$$

With:

- EE : embodied energy of the construction over ESL (including replacement of components)
- E_{USE}: total energy input of the construction during use
- E_{MT}: total energy input during the maintenance of construction and components (excluding replacement of components)
- E_{DIS}: total energy input during disassembly of construction
- E_{SORT}: total energy input during sorting of (sub) components, after disassembly or demolition
- $E_{TR,SORT}$: total transport energy of (sub) components to sorting site
- E_{EoL}: total energy input of end-of-life treatment of the construction, its (sub) components and/or building materials, over ESL

5.2 Conservation of embodied resources

Besides EE and E_{USE}, the energy input after using the construction or components has to be considered in an LCEA of buildings. When the consumed energy of different end-of-life options needs to be compared, Equation (2) can be contracted in the expression given by Equation (3). In this expression, end-of-life options are compared by looking at the conservation of the initial embodied energy (EE_0) and the energy needed to **reinvest** materials, elements, or (parts of) constructions in a possible second life [6]. As basis for the calculation of energy flows, the triple life cycle model (see Figure 1) is chosen.

$$\Delta EE = EE_0 - E_{RE\_INVEST} - E_{DIS} - E_{SORT} - E_{TR,SORT} \quad (3)$$

With:

- ΔEE conservation of embodied energy of a building material, element or construction
- EE_0: initial embodied energy of a building material, element or construction
- E_{RE_INVEST}: total energy needed to re-invest materials, components or (part of) construction in a second life cycle, in accordance with a chosen end-of-life treatment
- E_{DIS}: total energy input during disassembly of construction
- E_{SORT}: total energy input during sorting of elements and/or materials
- $E_{TR,SORT}$: total transport energy of elements and/or materials to sorting site

Table 1 provides guidelines to express E_{RE_INVEST} in an analytic way for each end-of-life option discussed in §2.1

Table 1: guide to calculate E_{RE_INVEST} in accordance with an end-of-life option (EoL) [6]

EoL option*	E_{EXTR}	$E_{TR,1}$	E_1	$E_{TR,2}$	E_2	$E_{TR,SITE}$	$E_{ASSEMBLY}$	$E_{ADD.}$
I	*x*	*x*	*x*	*x*	*x*	*x*	*x*	E_{LAND} + $E_{TR, LAND}$
II	*x*	*x*	*x*	*x*	*x*	*x*	*x*	E_{COMB} + $E_{TR, COMB}$ - E_{RECOV}
III	-	*x*	*x*	*x*	*x*	*x*	*x*	-
IV	-	-	-	*x*	*x*	*x*	*x*	-
V	-	-	-	-	-	*x*	*x*	E_{MT} + $E_{TR,MT}$
VI	*Energy input is restricted to the dismantled /demolished and additional components. See flow I to V*							E_{MT}
VII	-	-	-	-	-	-	-	E_{MT}

*With the following end-of life options: (I) land filling, (II) combustion, (III) feedstock recycling, (IV) material recycling, (V) reuse of elements, (VI) renovation or restoration of construction and (VII) reuse of construction.

Equation (3) gives information of conservation of embodied energy in absolute quantities. In a comparative assessment, however, it is interesting to view ΔEE relatively, as a percentage of the initial embodied energy. In such circumstances Equation (3) changes into:

$$\Delta EE = (EE_0 - E_{RE\_INVEST} - E_{DIS} - E_{SORT} - E_{TR,SORT}) / EE_0 \quad (4)$$

If the entire life span of a construction - or super component - is taken into account, the conservation of embodied energy (ΔEE) will change over time (t). This can be expressed with the following formula:

$$\Delta(\sum_{t=0} EE_t) = \frac{A}{\sum_{t=1} EE_{t-1}} \text{ with}$$

$$A = \sum_{t=0} (EE_{t-1} - E_{RE\_INVEST} - E_{DIS,t} - E_{SORT,t} - E_{TR,SORT,t}) \quad (5)$$

Until now only the conservation of **embodied energy** is discussed as a way of determining the environmental load of a building solution. The amount of **natural resources** (R), such as minerals, fossil fuels, fresh water, and land, can be inventoried as well. R is a fictive quantity and has to be filled in as a mass (m), a volume (V), or a surface (S) according to the type of resource under study. Complementary to Equation (5), the conservation of natural resources over the entire life span of a construction - assuming a building material, element or construction is reinvested - is expressed through Equation (6).

$$\Delta(\sum_{t=0} ER_t) = \frac{B}{\sum_{t=1} ER_{t-1}} \text{ with}$$

$$B = \sum_{t=0} (ER_{t-1} - R_{RE\_INVEST} - R_{DIS,t} - R_{SORT,t} - R_{TR,SORT,t}) \quad (6)$$

For the conservation of some natural resources, such as the amount of a particular mineral, the components R_{DIS}, R_{SORT} and $R_{TR,SORT}$ in Equation (6) can be left out.

In a similar way as in Table 1, guidelines can be set up for each resource under study. Since the choice of representative resources is case dependent a general flowchart is omitted in this theoretical framework.

5.3 Maximal conservation

It is assumed that each time the lifespan of (sub) components is reached, the same end-of-life treatment is executed and the old (sub) component is replaced by an identical new one. Furthermore, (dis)assembly of the temporary constructions will mainly be done manually or with limited mechanical means, such as a small crane.

These realistic suppositions facilitate the mathematical determination of conservation of (accumulated) embodied resources, Δ(EX) and $\Delta(\Sigma EX_t)$, where X is either the amount of energy (E) or natural resource (R). For this comparative assessment, Equation (4), (5) and (6) can subsequently be reduced to the following relationships:

$$\Delta EX_1 = (EX_0 - X_{RE\_INVEST}) / EX_0 \quad (7)$$

$$\Delta(\sum_{t=1} EX_t) = \Delta(\sum_{i=1}^{n} EX_i) = \Delta EX_1 / (\Delta EX_1 + n \cdot X_{RE\_INVEST}) \quad (8)$$

With:

EX_0	initial embodied resource
ΔEX_1	conservation of embodied resource after one replacement
Δ(ΣEX)	conservation of accumulated embodied resource over ELS of the construction kit
X_{RE_INVEST}	total amount of resource needed to re-invest materials, elements or (part of) construction in a second life cycle, in accordance with a chosen end-of-life treatment
ΣX_{RE_INVEST}	total accumulated amount of resource needed to re-invest materials, elements or (part of) construction in successive life cycles
n	number of replacements over the entire life cycle of the construction

It is assumed that at the end of the construction kit's life cycle all elements are reinvested in the same (sub) components. This means that the highest conservation rate for a particular embodied resource is obtained through the end-of-life treatment with the best performance with only a single replacement, i.e. at the end of the life cycle of the kit. In that case, maximal conservation is limited to ΔEX_1. The conservation of an embodied resource (X) after a single replacement is used here as an environmental performance indicator of the component. The calculated $\Delta(\Sigma EX)$ of a component or construction is compared with this limit. Note that the expression given in Equation (8) is also dependent of ΔEX_1. This means that the environmental performance of the studied system, based on a type of resources, is determined by only three parameters, i.e. EX_0, X_{RE_INVEST} and n.

6 DESIGN CASE

Due to the important dynamic requirements related to the use, transport and maintenance of mobile temporary constructions, these types of applications are the ideal objects to understand and environmentally assess the H-V design approach. In this paper the design of temporary multi-use infrastructure for peace supporting operations (PSO) is discussed.

6.1 Peace supporting operations

Preventing and/or resolving conflicts may require international assistance. In the framework of PSO, relief workers, coordinators, and relief infrastructure must be operational and ready to transport in a minimal amount of time (i.e. a few weeks). Since conflicts or other types of hazards can occur at any time, relief personnel has to manage quick interventions with a large number of varying parameters, such as the nature of the conflict or disaster, the characteristics of the affected area (e.g. climate and geography), the demography and needs of the local population. Furthermore, beside the unpredictability of disasters, relief organisations have to face the unknown course of events after the occurrence of the emergency. [10]

In more stable phases of relief, elaborated constructions are needed to support logistic facilities for the afflicted people and relief workers. Temporary working halls, offices, sanitary and eating/cooking facilities are only a few logistic facilities required to support the daily routine. Constructions made out of stiff components are used to provide a relatively secure environment for temporary applications of 6 months to several years. During that time interval these temporary constructions have to resist local climatic conditions and provide the necessary accommodation for daily functions. [7]

International relief is insufficiently prepared for these events, partly due to the inappropriate infrastructure [10]. An important cause of this deficiency is found in the lack of adaptability and versatility of existing prefabricated relief constructions. Most imported constructions and components have a limited potential to be adapted to the local conditions and/or to be reused in other relief phases.

6.2 A Meccano

Considering the variation in life cycle requirements, the design of PSO accommodation is orientated to several multi-use construction kits; composed of versatile and compatible (sub) components. With these components, a varied set of configurations can be assembled, with similar or totally different applications - including an ISO 20ft container to transport and store all elements to the construction site. Like in a Meccano box, only a limited number of different component types are selected. A basic construction kit is composed of:

- bearing frames and girders
- enclosing and dividing panels, with or without openings
- dry and reusable connection devices

In this study three typical PSO configurations are selected:

- sleeping accommodation (25m² floor area)
- offices (39m² floor area)
- canteen (253m² floor area)

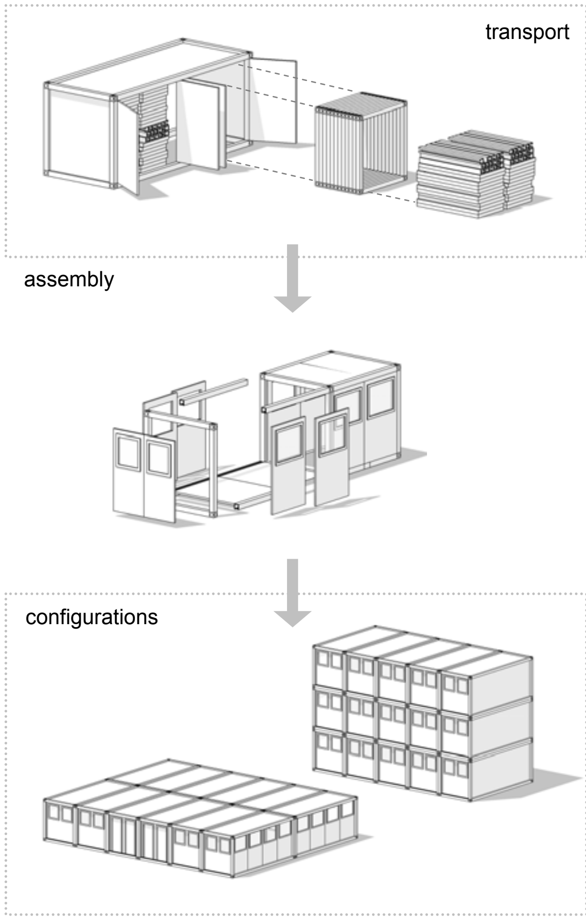

Figure 2: conceptual drawing of the designed multi-use construction kit for peace supporting operations

7 ENVIRONMENTAL LOAD ASSESSMENT OF DESIGN CASE

Durability of components plays an important role in the conservation of resources. Each replacement is related to a loss of resources. A longer replacement interval will consequently have a higher conservation index. Regular maintenance during use helps to lengthen the lifespan of components. Monthly cleaning procedures are taken into account in the inventory data.

Considering a construction kit's life cycle of 60 years, the figures in Table 2 and Table 3 prove that reusing components enhances the conservation of resources for most employed components. Elements that are vulnerable to wear and tear are identified during the design phase. By strategically reducing the amount of building material and (re)processing of these elements, the decrease in environmental load is targeted. For example, corners of the bearing frames are stress intensive knots that are more susceptible to mechanical impact than other skeleton elements. Consequently, wear and tear of these extremities will occur more rapidly than other parts. The loss of embodied resources, however, is negligible, since the corners are confined to small hollow elements, easily made out of cold formed profiled that are welded together. Compared to other parts of the bearing frame, corner elements are thus low in embodied resources, accumulated over the life span of the construction kit. Internal finishes, such as hardboard and linoleum faces are also susceptible to wear and tear. Statistically, they have to be replaced more often than other panel elements. However, due to small thicknesses of faces, the loss in accumulated embodied energy of panels is very small.

Table 2: conservation of **embodied energy** of the construction for each application per super component

	EE_0 [MJ/m² flr area]	ΔEE_1	$\Delta(\Sigma EE_i)$ REUSE	$\Delta(\Sigma EE_i)$ NO REUSE
sleeping acc.				
skeleton	*2337*	*9.3%*	*8.8%*	*2.5%*
skin	*530*	*38.5%*	*36.8%*	*9.6%*
office				
skeleton	*2299*	*9.3%*	*8.8%*	*2.5%*
skin	*488*	*38.5%*	*36.7%*	*9.6%*
canteen				
skeleton	*1428*	*9.3%*	*8.9%*	*2.5%*
skin	*417*	*39.3%*	*36.9%*	*9.9%*

Table 3: conservation of embodied mineral consumption of the construction for each application per super component

	Em_0 [kg/m² flr area]	ΔEm_1	$\Delta(\Sigma Em_i)$ REUSE	$\Delta(\Sigma Em_i)$ NO REUSE
sleeping acc.				
skeleton	*67*	*87.2%*	*86.3%*	*63.0%*
skin	*22*	*90.3%*	*90.3%*	*60.9%*
office				
skeleton	*66*	*87.2%*	*86.3%*	*63.0%*
skin	*20*	*90.3%*	*90.3%*	*60.9%*
canteen				
skeleton	*41*	*87.2%*	*86.5%*	*63.1%*
skin	*17*	*90.3%*	*90.3%*	*60.9%*

Comparing the consumption of embodied energy of skeleton and skin elements, a low ΔEE_1 for the steel bearing structure of all configurations is discerned. Although (re)processing of steel has a high recovery rate of minerals, it is an energy intensive procedure. Furthermore, the initial steel making procedure already takes into account 25% steel scrap material, which makes the energy consumption differences between the initial steel element and the reinvested one even smaller. ΔEE_1 of panel elements is higher, since the combustion of timber panel elements comes along with a recovery of energy - calculated on basis of the higher heating value of the incinerated material. Maximal recovery rates of minerals of 90% for the panel elements are discerned due to the high recyclability of the chosen industrial materials, i.e. steel as the external cladding, stone wool as insulation layer and glass for the windows.

8 CONCLUSIONS

Combining reuse of components with high durability of basic elements clearly delivers the best conservation of embodied resources for the temporary constructions under study. These dynamic features are provided by the detailed design of a Meccano kit. The environmental assessment delivers a proof-of-concept of the environmental surplus value of the H-V design approach. The approach is also applicable for other types of constructions.

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Eco Concrete Stones with TiO2 for Atmospheric Decontamination

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Abstract

In the present work the degradation of nitrogen oxides (NO_x) by concrete paving stones containing TiO_2 is studied. A kinetic model is proposed to describe the photocatalytic reaction of nitric oxide (NO) in a standard flow laminar photoreactor irradiated with UV lamps. In addition the influence of several parameters that can affect the performance of these stones under outdoor conditions are investigated, such as irradiance, relative humidity and wind speed. The kinetic parameters present in the NO reaction rate are estimated employing experimental data obtained in the photoreactor. The model predictions employing the determined kinetic constants are in good agreement with the experimental results of NO concentration at the reactor outlet.

Keywords:

Heterogeneous photocatalysis, Air purification, Concrete roads, Nitrogen oxides, Kinetic model

1 INTRODUCTION

Heterogeneous photocatalysis represents an emerging environmental control option for the efficient removal of chemical pollutants and it can be applied to water and air purification. This process involves a nano-solid semiconductor catalyst, regularly titanium dioxide (TiO_2), which is activated with ultraviolet light of the appropriate wavelength. For various reasons repetitively reported, titanium dioxide in the form of anatase has been the preferred choice due to its strong oxidizing power under UV irradiation, its chemical stability and the absence of toxicity. These reactions are very attractive for treating pollution problems because: (1) in the vast majority of the cases transform pollutants into innocuous products and (2) have very low selectivity, thus permitting the treatment of a wide range of contaminants.

Nitrogen oxides (NO_x) is the generic term for a group of highly reactive gases, most of them emitted in air in the form of nitric oxide (NO) and nitrogen dioxide (NO_2). Nitrogen oxides form when fuel is burned at high temperatures, as is the case in combustion processes in automobiles. NO_x causes a wide variety of health and environmental impacts, like the formation of tropospheric ozone and urban smog through photochemical reactions with hydrocarbons. Furthermore, NO_x together with SO_x (sulfur dioxide and sulfur trioxide) is the major contributor to the “acid rain”, one of the most serious environmental problems across the world. Thus, NO_x emission has been a focus of environmental regulations, especially in the ozone non-attainment areas.

The European Union (EU) has taken important steps over the past decade leading to a decrease in the emissions to air and water of a number of pollutants. One of its directives (1999/30/EC) [1] establishes limit values for concentrations of sulphur dioxide, nitrogen dioxide and oxides of nitrogen, particulate matter and lead in ambient air. Some of the pollutant emissions have since become more or less manageable; however particulates, NO_x and smog are still problematic.

To date, a number of researchers have investigated the dynamics of the photocatalysis of nitrogen oxides. While some of the NO_x control methodology is to reduce NO_x back to N_2 [2], another approach is to oxidize NO to NO_2 and HNO_3 along the general direction of nitrogen fixation [3-9]. The development of innovative materials that can be easily applied on structures, with both de-soiling and de-polluting properties, is a significant step towards improvements of air quality. The use of TiO_2 photocatalyst in combination with cementitious and other construction materials has shown a favorable effect in the removal of nitrogen oxides [10].

In the present work the degradation of NO_x compounds employing concrete paving stones with TiO_2 to be applied in road construction is studied. The experiments were carried out in a laminar flow photoreactor designed according to the standard ISO 22197-1 (2007) [11] to assess these kind of photocatalytic materials employing NO as the pollutant source. A kinetic model is proposed to describe the photocatalytic oxidation of NO_x and the influence of several parameters that can affect the performance of these stones under outdoor conditions, such as irradiance, relative humidity and wind speed. A reaction rate expression for the NO oxidation is postulated and the kinetic parameters are determined employing the experimental data. Finally the model predictions with the estimated kinetic constants are compared with the experimental results obtaining a good agreement between them.

2 EXPERIMENTAL SETUP

The standard ISO 22197-1 (2007) [11] serves as a sound basis for measurements, its recommendations were largely followed for the practical conduction of the present study. The applied apparatus is composed of a planar reactor cell housing the concrete stone sample, a suitable UV-A light source, a chemiluminescent NO_x analyzer, and an appropriate gas supply (Figure 1). Table 1 shows the main characteristics, dimensions and operating conditions of the experimental setup that were employed to carry out the photocatalytic NO degradation experiments.

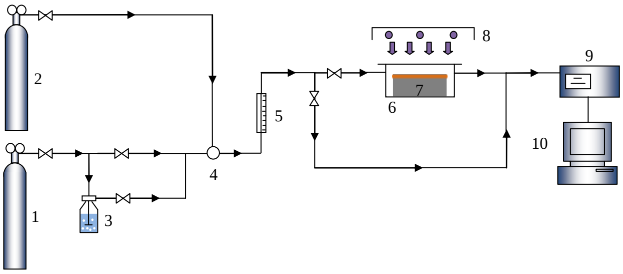

Figure 1: Schematic representation of the experimental setup. 1. Synthetic air. 2. NO source. 3. Gas washing bottle. 4. Temperature and relative humidity sensor. 5. Flow controller. 6. Gas photoreactor. 7. Paving stone sample. 8 Light source. 9. NO_x analyzer. 10. Computer.

Description		Value
Reactor	Length (L)	2 dm
	Width (B)	1 dm
	Height (H)	0.02-0.04 dm
	Volume (V_r)	0.04-0.08 dm^3
Photocatalytic Stone	Length (L)	2 dm
	Width (B)	1 dm
UV Lamps	Input Power	25 W
	Emission Wavelength	300-400 nm
Flow Rate (Q)		3-5 l min^{-1}
Relative Humidity (RH)		10-80 %
NO Inlet Concentration ($C_{NO,in}$)		0.1-1 ppm
Irradiance Flux (E)		0.3-13 W m^{-2}

Table 1: Experimental setup main characteristics and operating conditions.

The core of the experimental setup is a gas reactor allowing a planar sample of the size 100 x 200 mm^2 to be embedded (Figure 2). Furthermore, the reactor is made from materials which are non-adsorbing to the applied gas and can withstand UV light of high radiation intensity. On top the reactor is tightly closed with a glass pane made from borosilicate, allowing the UV-radiation to pass through with almost no resistance. Within the reactor the planar surface of the specimen is fixed parallel to the covering glass, leaving an alterable slit height H for the gas to pass through. The applied light source is composed of three fluorescent tubes Philips Compact S of each 25 W, emitting a high-concentrated UV-A radiation in the range of 300 to 400 nm with maximum intensity at about 345 nm. All fluorescent tubes can be adjusted in irradiance. With the help of a calibrated UV-A radiometer (RM – 12 Dr. Groebel UV-Elektronik GmbH) the irradiance was adjusted at the sample surface.

For the conduction of the experiments, two different types of gas, filled in standard gas cylinders, are necessary. For the pollution of the sample surfaces, nitric oxide (NO) is deployed. The used gas is composed of 50 ppm NO which is stabilized in nitrogen (N_2). As the concentration of gas, finally applied to the sample, will be adjusted to the NO inlet concentration (1.0 - 0.1 ppm), only small quantities of this gas are required. As transport fluid synthetic air, being composed of 20.5 vol.-% of oxygen (O_2) and 79.5 vol.-% of nitrogen (N_2), is deployed.

Since the gas cylinders are under high pressure, the gas needs to pass a pressure reducing valve before entering the system. Here, pressure is first reduced to 0.3 bar. Before the two gas flows are merged, the model contaminant has to pass a high precision valve in order to adjust the pollution concentration ($C_{NO,in}$) to the sample. The NO concentration can be monitored with the NO_x analyzer, connected to the outlet of the reactor box. Furthermore, the synthetic air will be conveyed through a gas-washing bottle, filled with demineralized water, in order to keep the relative humidity of the supplied gas constant. Using a split gas flow, with one line passing a valve before the gas-washing bottle, one can realize the desired humidity. Behind these two stages both gas flows, polluted and transport fluid, are mixed. With the help of a flow controller a volume flow of 3.0 or 5.0 l/min is adjusted.

The gas, mixed and humidified this way, enters the reactor and is conveyed along the illuminated sample surface. At the opposite site of the reactor the gas leaves the chamber and is transported to a flue or outside with the help of an exhaust air duct. The NO analyzer sources the reacted test gas from this exhaust line. An adequate dimensioning of the hose line and, possibly, the installation of non-return valves prevents from suction of leak air from outside via the hose line to the analyzer.

For the gas analysis a chemiluminescent NO_x analyzer (Ambient NO_x Monitor Horiba. APNA – 370) was deployed. The analyzer is measuring the NO_x and NO concentration in steps of 5 sec while the corresponding NO_2 concentration is computed by the difference of the previous two. During the measurement the analyzer is constantly sampling gas with a rate of 0.8 l/min. The detection limit of the deployed analyzer is at about 0.5 x 10^{-3} ppm.

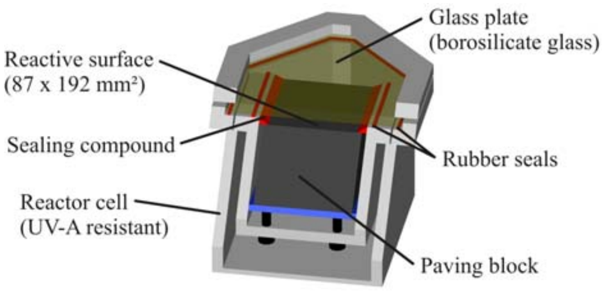

Figure 2: Schematic diagram of the gas photoreactor.

For the development of a reaction model and the herewith related experiments one sample, a paving stone, was used. This way differences in measurement results due to varying surface roughness or unequal distribution of catalyst can be neglected. In preparation of each measurement the sample surface is cleaned in order to remove fouling, contamination and potential reaction products due to a previous NO_x degradation. The cleaning process is always executed following a specified scheme using demineralized water. Subsequently, the sample is dried in a drying oven for 24 hours. For the measurement, the sample with the reactive surface upwards is placed in the reaction chamber. With the help of an elastic sealing compound all gaps and joints around the sample are caulked that way that the fed air could only pass the reactor along the reactive sample surface. In doing so, a metal sheet of the dimension 87 x 192 mm^2 was deployed as a template for the sealing. The active sample surface was kept exactly identical for all measurements this way.

After assembling the sample the reactor is closed and the gas supply is started. The UV-A source is switched on as well in order to start the radiation stabilization, but the reactor stays covered to prevent first degradation. With the help of the controls the flow rate and the relative humidity are adjusted. The supplied NO concentration is adjusted to the desired inlet concentration, which is checked by the analyzer. When these conditions appear to be stable the data acquisition is started. Now, for the first 5 minutes the system remained unchanged in order to flush the reactor chamber and to finally eliminate an increase of UV-A radiation. During this time the measured NO outlet concentration of the reactor was first decreasing and then approaching again the original inlet concentration. This phenomenon describes the saturation of surface with NO as well as the non contaminated air removal from the reactor and was found to be a function of flow velocity, inlet concentration and surface character of the sample. After this period of time, the cover sheet was removed to allow the UV-radiation passing through the glass. This was very quickly responded by by the analyzer. The degradation for the uncovered reactor lasted for 30 minutes, then the reactor was covered again and the data acquisition was continued for further 5 minutes. Within the last minutes of measurement the NO and NO_x concentrations should ideally return to the original scale. As the reactor can be bridged, i.e. the pollutant can be directly transferred to the analyzer without passing the reaction camber, the NO inlet concentration at the end of a measurement was always compared with the original concentration at the beginning of the measurement. In this way measurement errors due to creeping NO concentrations during the measurement are prevented. An example of a representative experiment result is shown in Figure 3, where the different steps mentioned above can be observed.

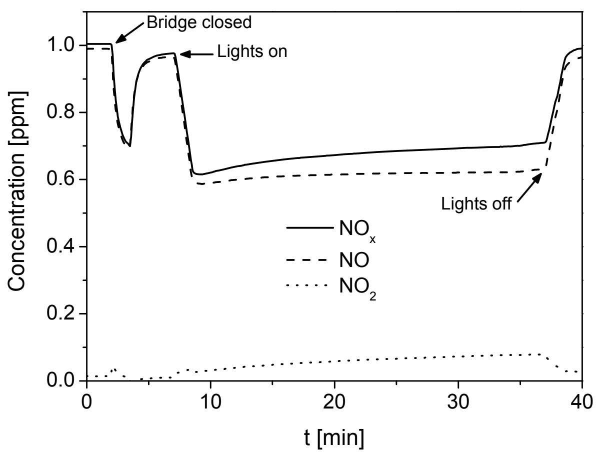

Figure 3: Representative experimental result. H = 3 mm. Q = 3 l min^{-1}. $C_{NO,in}$ = 1.0 ppm. RH= 50%. E = 10 W m^{-2}.

3 THEORETICAL MODEL

The kinetic expression proposed for the NO degradation reaction rate is the corresponding to the Langmuir-Hinshelwood model [9, 12], which is widely employed for the photocatalytic degradation of other contaminants [13-15]. However the reaction rate should be expressed as a superficial rate for a gas-solid heterogeneous system [16, 17]. In addition, water competes with NO for free active sites at the catalyst surface and therefore it can be considered as an additional reactant [15]. Following this model applied to a heterogeneous reaction, the Langmuir-Hinshelwood kinetic model for NO disappearance rate per unit area of active surface reads:

$$r_{NO} = -\frac{kK_{NO}C_{NO}}{1+K_{NO}C_{NO}+K_wC_w} \qquad (1)$$

Where r_{NO} is the superficial reaction rate (mole dm^{-2} min^{-1}) of NO. C_{NO} and C_W the corresponding molar concentration (mole dm^{-3}) of NO and water. k is the reaction rate constant (mole dm^{-2} min^{-1}). K_{NO} and K_W are the adsorption equilibrium constant (dm^3 mole^{-1}) for NO and for water respectively.

Regarding the UV light effect, it is supposed that the irradiance only has an influence on the reaction rate constant (k). Therefore a mathematical expression of the reaction constant k in function of the radiative flux E is proposed:

$$k = k'\left(-1+\sqrt{1+\alpha E}\right) \qquad (2)$$

With k' (mole dm^{-2} min^{-1}) and α (dm^2 W^{-1}) being factors to be fitted from the experiments. This expression takes account of the linear and the square root dependency of the reaction rate with the light intensity that have announced in several publications [16] for high and low irradiance respectively. When UV-radiation is absent, i.e. $E = 0$, the reaction rate becomes zero. For small E , Eq. (2) tends $k'\alpha E/2$, and for large E it tends to $k'\sqrt{\alpha E}$.

The NO balance equations for a plug flow reactor reads:

$$v_{air}\frac{dC_{NO}}{dx} = a_v r_{NO} \qquad (3)$$

where v_{air} is the air velocity (dm min^{-1}) in the reactor and a_v is the active surface area per unit reactor volume (dm^{-1}). The reactor inlet condition is:

$$C_{NO}(x=0) = C_{NO,in} \qquad (4)$$

4 KINETIC PARAMETERS ESTIMATION

To solve the NO mass balance with the complete kinetic expression, a numerical method needs to be applied. Therefore a forward discretization of the differential equation (Eq. (3)) was performed applying the Euler method. Then the non linear optimization of all kinetic parameters present in the reaction rate can be achieved employing the "solver" tool of Excel and using the experimental results of the NO outlet concentration under different operating conditions of the photoreactor (varying the flow rate, reactor slit height, NO inlet concentration, relative humidity and irradiance). The result of this estimation is shown in Table 2.

Parameter	Units	Value
k'	mole dm^{-2} min^{-1}	7.24 x 10^{-10}
α	dm^2 W^{-1}	1.40 x 10^6
K_{NO}	dm^3 mole^{-1}	2.50 x10^{10}
K_w	dm^3 mole^{-1}	7.67 x 10^5

Table 2: Non linear parameters optimization (based on 36 experimental results).

5 EXPERIMENTAL RESULTS VERSUS MODEL PREDICTION

It is possible to analyze the effect of different operating variables on the system by resorting the estimated kinetic parameters from the complete model. This analysis can include a comparison between simulated values obtained with the model and experimental measurements.

Figure 4 shows the model predictions and the experimental data corresponding to the NO outlet concentration in function of the NO inlet concentration to the reactor for two different flow rates. When the inlet concentration of NO increases, NO outlet concentration rise as well. However, as expected, decreasing the initial concentration of the pollutant the final conversion of the reacting system increases.

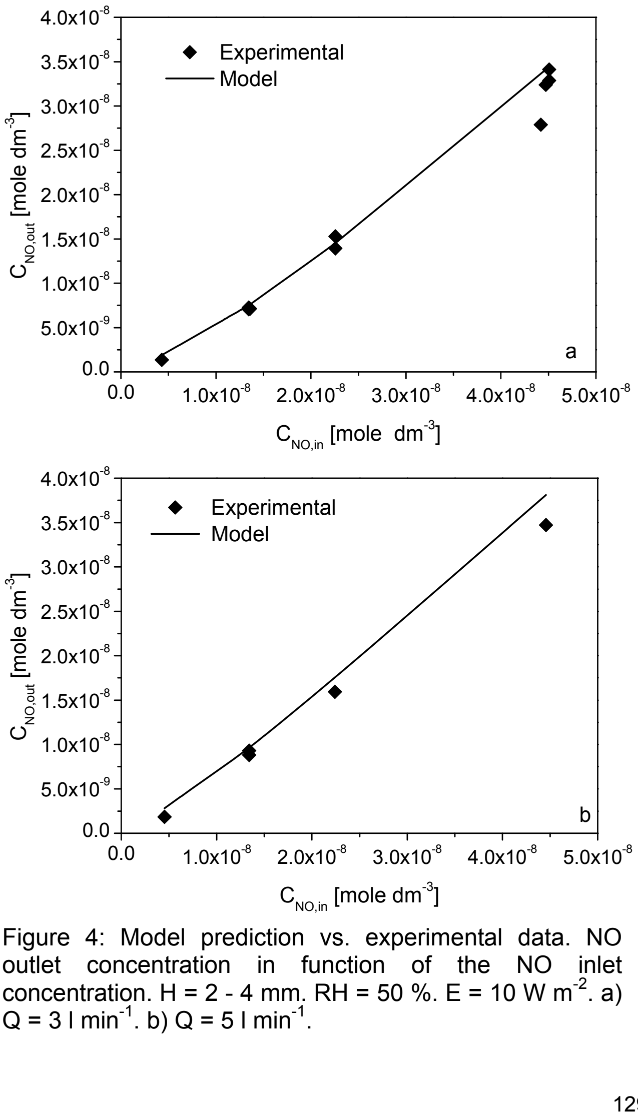

Figure 4: Model prediction vs. experimental data. NO outlet concentration in function of the NO inlet concentration. H = 2 - 4 mm. RH = 50 %. E = 10 W m^{-2}. a) Q = 3 l min^{-1}. b) Q = 5 l min^{-1}.

The effect of the flow rate is possible to analyze comparing Figures. 4(a) and (b). When the flow rate is increased the resident time in the reactor decreases. Therefore, for low flow rates a larger conversion of the pollutant is observed.

Regarding the irradiance and relative humidity effect, Figures 5(a) and (b) show the obtained results varying these two parameters, respectively. When the irradiance is increased a higher conversion of the systems is achieved. However when the relative humidity is enlarged water competes with NO for the same active site and the NO consumption declines.

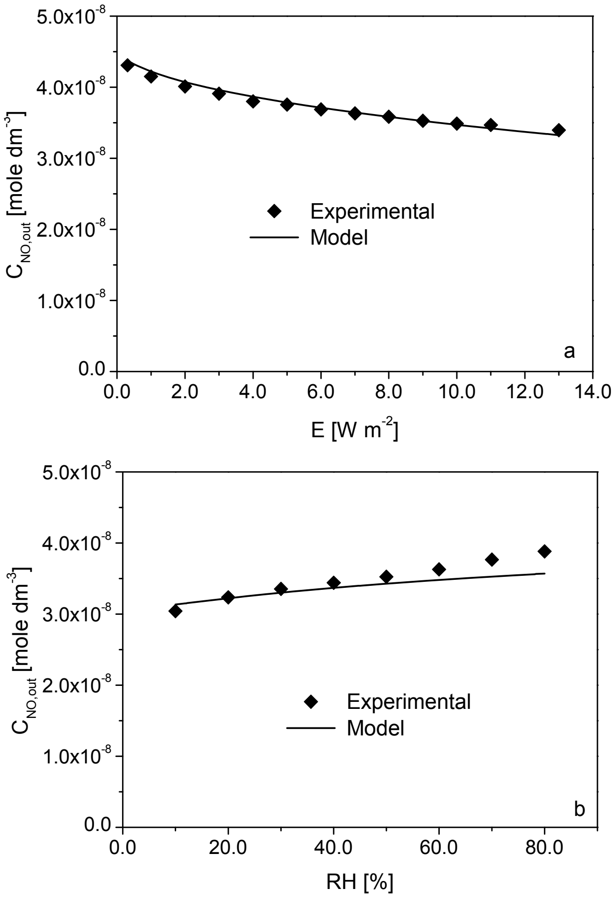

Figure 5: Model prediction vs. experimental data. a) NO outlet concentration in function of the radiative flux. b) NO outlet concentration in function of the relative humidity. $C_{NO,in}$ = 1 ppm. Q = 3 l min^{-1}. H = 3 mm.

6 CONCLUSION

In the present work, a kinetic study of the photocatalytic degradation of nitrogen oxides was conducted. A heterogeneous kinetic expression for the NO degradation was proposed. Several experiments were carried out according to a suitable ISO standard for photocatalytic materials assessment employing only NO as a contaminant. Different operating conditions were selected to perform the experiments (NO inlet concentration, reactor height, flow rate, irradiance flux and relative humidity). Employing these experimental data and the reaction rate expression, the kinetic parameters were estimated for a numerical solution of the governing equations in the reactor, based on Langmuir-Hinshelwood kinetics. In all cases, a very good correlation between the experimental data and the computer simulation with the estimated kinetic parameters was obtained.

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Construction Process Assessment or "Black Box Opener"

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Abstract

The construction industry and related ones are considered the world's largest industrial employer and natural resources consumer. 50% of all materials extracted from the earth are transformed into construction materials and products. When these materials enter the waste stream, they account for some up to 57% of all waste generated prior to recycling, recovery or final disposal.

In spite of these alarming conditions, very little detailed knowledge currently exists about the origins, distributions and degrees of significance of construction wastes, although construction managers must by necessity always attempt to minimize waste (and thereby optimise the use or resources), construction materials and waste do not uniformly receive appropriate consideration in the construction industry. Those wastes and losses arise very often from inadequate design practices and management or poor housekeeping.

The main goal of the study is to gain insights into the traditional and industrialised construction processes in order to analyse the performance of the production system and its relation with the environment. This paper presents some tools that have been prepared, in order to analyse amounts of waste, causes for its production, different factors and their significance degrees that influence the production of waste.

Keywords:
Construction industry, material management, prevention, waste, material flows

1 INTRODUCTION

The construction industry and related ones are considered the world's largest industrial employer and natural resources consumer. 50% of all materials extracted from the earth are transformed into construction materials and products [1, 2].

Construction projects are intricate, time consuming undertakings. The total development of a project normally consists of several phases, participation of many stakeholders and dozens of operations. Besides, it requires human resources that should be skilled and materials and equipments available when needed. To some degree each construction project is unique, each structure is tailored to suit its environment, arranged to perform its own particular function, and designed to reflect personal tastes and preferences. The contractor sets up the "factory" on site and to a large extend and custom builds each structure. Consequently, construction projects are typified by their complexity and diversity and by the no standardized nature of their production. The use of factory made modular units may diminish this individuality somewhat, but it is unlikely that field construction will ever be able to adapt completely to the standardized methods and product uniformity of assembly line production [3].

The construction process converts materials and energy into products and residual products and when these materials enter the waste stream, they account for some 50% of all waste generated prior to recycling, recovery or final disposal [4].

Waste in the construction industry has been the subject of a number of research projects in different countries and the literature review indicated that:

1. The availability of data on material waste in the building industry was relatively scarce.
2. Construction materials, labour and waste production do not uniformly receive appropriate consideration and very little detailed knowledge currently exists about the origins and distributions of construction wastes.
3. The number of empirical studies in different countries is small and mostly from developed countries, very few studies were found from developing countries.
4. Most of the studies investigated a fairly limited number of materials in a few construction sites.
5. Comparing the results of those studies is difficult, due to the different construction technologies involved, and also because distinct measurement procedures were adopted in each of them.
6. Many of the studies have focussed on design of sustainable buildings and the end of pipe solution for waste management, mainly recycling of waste.
7. Only scarcely information was found related to the issue of material management by contractors .

Based on the literature findings, a research was planned with the objective to investigate the construction sector in a developing country, Costa

Rica, focusing on construction materials (mainly concrete, steel and wood) and processes. The research tries to look into production processes in order to determine waste quantities and to explain the major factors that influence the production of solid waste by means of analysing the situation of material management during the procurement of buildings.

A first study took place and aimed to provide a baseline understanding related to construction waste in Costa Rica, its quantities, composition, causes, as well as, motivators and barriers for achieving a more sustainable activity. Very limited information was found and the existing one has discrepancies. The survey helped to find the causes of waste generation, which are related to design factors and management of materials, according to the respondents.

A second study is planned with the objective to analyse the construction process in the Costa Rican context and identify the quantities of waste produced while the procurement of buildings, the variables that influence the production of waste and score those attributes.

This paper is about the tools that have been prepared to approach the study. Therefore, its objective is to discuss the appropriateness of the tools for the analysis of the construction processes or tools to “open the black box”.

2. Process assessment or “black box” opener

The construction process is a system that contains a set of objects with mutual relationships, which are the physical flows and their transformation This system can be considered as a “black box” that when opened, it contains subsystems that are part of the original system.

Figure 1 represents the production process under study, in which semi-finished materials and products are transformed into products (edifices). Every production process needs ancillaries such as energy carriers and materials. This production process not only creates products, but also unintended residuals, such as byproducts and waste.

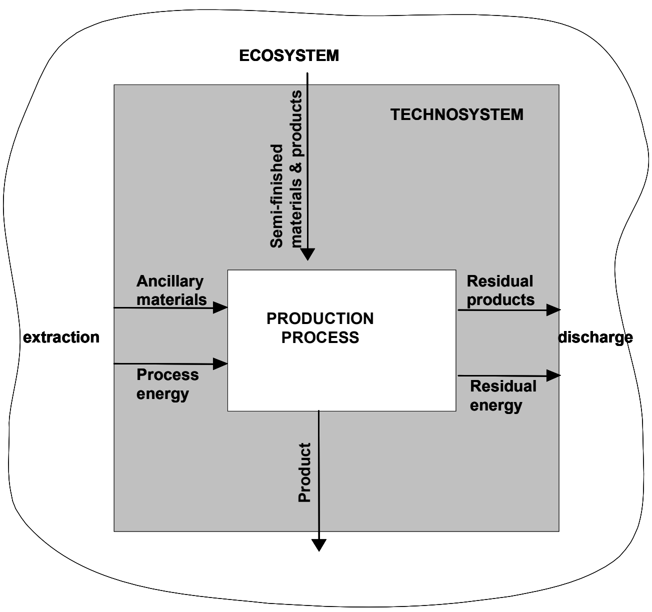

Figure 1. Simple linear technosystem. (Based on Lambert) [5]

A way to analyse the flows and stocks in this so called technosystem is by using Material Flow Analysis (MFA), which is a systematic procedure that connects the sources, the pathways and the intermediate and final sinks of materials [6]. A MFA delivers a complete and consistent set of information about all flows and stocks of a particular material within a system. Through balancing inputs and outputs, the flows of wastes and environmental loadings become visible, and their sources can be identified [7]. But measuring just flows is insufficient to understand the processes that take place in a production system. Therefore, the description of the flows is important as well as the comprehension of the processes behind those flows.

In order to describe the internal transformations of materials and energy to assess the efficiency (and sustainability) of the technosystem a survey and explanatory multi-method case studies have been developed with the purpose to apply the tools in a real life context. The assessed projects will be in Costa Rica, and they will have the peculiarity of projects built with traditional and industrialized (up to some pre-fab extend) systems. The projects will be selected for residential middle size constructions, located in the Great Metropolitan Area.

2.1 Tools development

The tools developed are based on an extensive literature research in which various authors pointed out that design factors and management are the main sources of miuse of resources and production of waste. Five research propositions are developed in order to analyse the sub-processes, as well as, a quantitative method to analyse the amount of waste produced during the procurement of buildings.

2.1.1 Cause 1: design factors

The literature review demonstrates that the lack of quality in construction activities and the waste generated on site can be attributed to: the imperfections on the design and specifications [8], to structural design being poor in terms of standardization and detailing, change of orders, detailing mistakes, the need to cut blocks or other materials due to the lack of modular coordination in design, poor integration of building subsystems during the design stage, poor detailing of design, lack of optimisation during design in the use of resources, imprecise specification of components, and lack of site layout planning [9, 10, 11, 12, 13, 14, 15, 16, 17, 18].

Research Proposition 1: The use of design measures and concepts can reduce construction waste. (Modular coordination and standardisation, minimizing the use of temporary works, avoiding late design modifications, providing more detailed design, introduction of improved design, dimensions to match with the material size standards).

The aim of this sub-study is to examine the aspects presented in the research proposition 1, which according to some authors influence and motivate the design of the projects and the importance given by the designers of projects to environmental issues.

The information will be collected using a questionnaire, which will be applied to architects, designers, civil engineers or professionals in charge of the design of the buildings on the companies where the case studies will take place.

2.1.2 Management factors

One of the first studies found in literature related to materials wastage dates from 1976 in which Skoyles started to analyse the misuse of materials by the construction sector. His conclusion was that materials and labour spent on handling them to the fixing position, account for nearly half the cost of traditionally constructed building and the waste occurring in practice is, on average, about double the losses generally assumed or allowed for in estimating. Since then, the importance of materials management and control has been established. Wyatt (1978) suggested that wastage of materials arise from inadequate monitoring or administration, or poor housekeeping [20]. He mentioned the importance of monitoring the flow of materials and the data associated with them, such as their quantities and inventory levels, they asserted that the main problem is the lack of up to date relevant information.

Material management and labour productivity has also been studied and it has been estimated the work-hour losses resulting from ineffective practices. The authors argued that formal material management programmes have the potential to yield significant construction cost savings due to the fact that material resources constitute a large portion of a project's total costs [13, 20, 21, 22]. Some authors have explained the benefits of the application of materials management and control systems in order to: increase productivity and avoid delays due to the availability of the right materials prior to work commencement and the ability to plan the work activities according to the availability of materials [23, 24].

Gavilan and Bernold [18] emphasized that waste reduction is the best and generally most economical way to improve the use of materials. They concluded that more detailed planning of materials and process requirements and better material handling are needed in order to reduce construction waste. Bossink and Brouwers [9] came to the same conclusion in which they analysed different causes for the production of waste and the most significant ones are related to management, being the most important material handling and operational issues.

Research Proposition 2. Materials' control and management do not have enough attention at the company level.

The aim of this sub-study is to analyse the material management system present at the company level with the participation of professionals from the head office, personnel on site, manufacturers and suppliers.

A checklist has been prepared that will be used as a guide to check on site material management practices, as well as a guiding tool to ask questions about management practices to managers at the head office, on site, manufacturers and suppliers.

Research Proposition 3. Various sources have a different yet significant effect on construction site waste generation

The aim of this sub-study is to determine main sources of construction waste and to ascertain the levels of importance of those waste sources.

The information will be collected by means of a survey applied to senior workers from construction companies' engineers, academics and practitioners at construction sites. They will be asked to rate pre-determined attributes according to their potential contribution to the generation of waste on site, from the experience of their companies. The respondents will be invited to add new attributes if necessary.

2.1.3 Material flow analysis

Materials pass through a number of handling processes from their use to their final disposal. These processes can induce various factors affecting materials management effectiveness, thus the proper flow of these processes is important.

Shen et al [26] developed a descriptive model for analysing the flow of materials in the construction sites, which provides with a systematic way for describing the generation of waste during the building processes. Ming Lu et al [28] indicated that the model fails to show the matching, queuing, and transit of various resources and the intricate interdependencies between different processes. Instead they used the free flow-mapping model as a basis to develop a process mapping technique that could represent the intricate logical and technological constraints and complex interdependent relationships between components of a typical handling system in construction.

In the case study of Costa Rica, the free flow mapping technique is chosen for observing and drawing the movements of the materials (wood, steel and concrete). Attention will be paid to matching, queuing and transit of the various materials trying to reduce the gap between the simple mapping of the materials and the failures stated by Min Lu et al.

Material Mismanagement

Mismanagement of materials on site emerges as one of the main causes of waste. Substantial losses are caused by inadequate transportation, unloading and stacking of materials, unsuitable packaging, poor ground conditions, equipment mal functioning and due to craftsmen's errors. Field data indicated that most material wastes came from one of 2 sources: leftover from cutting stock materials to fit and nonreusable of materials that are not part of the building (nonconsumables) [13, 15, 18, 25, 26].

Research Proposition 4: Material management has a positive influence in the reduction of construction waste.

Research Proposition 5. Waste is produced due to a combination of events rather than an incident occurring in one operation.

The aim of this sub-study is to examine the flow processes of construction materials (wood, steel and concrete) on site by using a free-flow mapping presentation technique and a checklist. The information in mapping includes 5 elements: material supply, waste source, waste facilitator, waste processing and waste destination. The observations with the checklist and discussions (with site management staff or building workers) on the practices will be oriented to the following topics and other ones arising during the study: coordination and information, waste handling and sorting actions, reduction, reuse and recycling of waste practices, pollution and safety.

2.1.4 Quantitative analysis of waste production

Waste in the construction industry is important not only from the perspective of efficiency, but also concern has been growing in recent years about the adverse effect of the waste of building materials on the environment

Various researchers have investigated quantities of construction waste materials. Skoyles [26] and Picchi [27] used the bill of quantities but it has the limitation that some of the materials are considered as waste while they might have been used in other projects.

Gavilan and Bernold [18] presented different approaches to analyse the generation of waste as well as its limitations. Approach 1 is "Cradle to grave" in which observations of construction materials are traced. This would be the most accurate way of making the observations but it is unmanageable.

In the approach 2 the end product (construction waste) would be inspected and the sources of waste can be determined by careful scrutiny, questioning of the work crews, and deduction. It has the limitation that the piles are difficult to assess.

Approach 3 is a modification of approach 1. Instead of tracing the path of every material through the process, a selected number of bricks, or lumber pieces, could be marked and traced from the start to the end. This would place proper emphasis on the flow of the material through the construction process as well as providing a sample of manageable size. The limitation with this approach is that the causes of construction waste are not necessarily uniformly distributed throughout a stack of materials.

Approach 4 focuses on workers and not on materials. A worker would be observed for a given period of time and the amount of waste s/he produces and the reason could be carefully tracked. This was an adaptation of the method time measurement technique used in evaluating worker and crew efficiency.

The advantage of this approach is that it is simple and that the causes of the waste will be very easy to identify but it has the limitation is that direct observation is not always possible though this is the single most effective way to ascertain the causes of construction waste.

Formoso et al. [13] proposed an approach in which the sites can be directly observed during a period of the processes (4-5 months). At the beginning of the period (date A), initial data collection is carried out by the research team. This involves measuring all construction work in which the 3 materials to be analysed (concrete, steel and wood) participated as well as existing inventories for those materials. At the end of the period (date B) a similar data collection is undertaken.

Between dates A and B, data is directly collected, doing the site observations during the working hours. The amount of materials delivered or withdrawn from the site before date A is obtained by material supply records.

According to the authors the data collection and processing procedures developed for the study was fairly successful as research methods, but they are too expensive to be directly adopted by construction companies.

In the case of the Costa Rican study, this procedure will be adapted with the support of students from the Civil Engineering departments of two universities. A protocol has been developed in order to do the analysis

3. Conclusions

Disposal sites in different parts of the world show that up to 57% of the composition of the waste arriving to the site is material from construction activities.

In the literature review, the most important topics related to the generation of construction waste are associated to design factors and material management systems.

The minimisation of waste should start at the beginning of the process which means at the design stage, taking into account: modular coordination and standardisation, minimizing the use of temporary works, avoiding late design modifications, providing more detailed design, introduction of improved design, dimensions to match with the material size standards, among others.

In relation to material management, many companies do not know the amounts and causes for the generation of waste, they are unaware of the amounts of waste produced and its causes, and by understanding them effective minimisation plans can be established.

Material management practices can help to reduce the amount of waste produced while building but it is necessary to understand the complexity and the relations between materials as inputs, processes in which they take and waste as outputs. Therefore, this study might give ideas on the degrees of significance of each factor that influences the production of waste. The analysis of those significance degrees would allow focusing on some of the causes that affect the system.

As already mentioned the objective of the presentation of this paper is to discuss with researchers, working in the field of construction materials stewardship, the propositions and the tools that have been prepared in order to analyse the different subsystems present in the process of building an edifice. Besides, another objective is to talk about the different possibilities to quantify the amounts of waste produced during the procurement of buildings, its opportunities and limitations.

There are no conclusions yet, but as mentioned by Formoso et al. (2002), measuring waste is an effective way to assess the performance of production systems because it usually allows areas of potential improvement to be pointed out and the main causes of inefficiency to be determined. That is the main goal of the whole study, to determine construction waste generation in a newly starting industrialised setting using Costa Rica as a case study.

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Constitutive modelling of viscoelastic behaviour of CNT/Polymer composites

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Abstract

The nanocomposites exhibit high electrical conductivity, significant third order non-linear optical behaviour and electroluminescence, while having substantially improved mechanical strength relative to the neat polymer. Since the experimental techniques are so expensive, the development of analytical models those are capable of predicting the time-dependent viscoelastic behaviour of such nanocomposites is essential. In this paper, the constitutive relation and linear viscoelastic behaviour of NTRPC are studied using methods of micromechanics and nanomechanics. First, the effects of volume fraction, aspect ratio and orientation of carbon nanotubes (CNTs), on the overall elastic properties of NTRPC are obtained through a variety of micromechanical techniques. Secondly, by incorporating the Dynamic Correspondence Principle (DCP), the elastic solution is extended to solve the related linear viscoelastic problem.

Keywords:

Carbon nanotubes, Nanocomposites, Viscoelasticity, Mechanical properties

1 Introduction

Polymer composites reinforced by carbon nanotubes (CNTs) have been extensively researched for their high strength and stiffness properties [1]. The high strength and elastic modulus, fibrous shape and large aspect ratios of these nanotubes (NTs) make them a very promising candidate as the ideal reinforcing fibers for advanced composites with high strength and low density [2]. The nanocomposites exhibit high electrical conductivity, significant third order non-linear optical behavior and electroluminescence, while having substantially improved mechanical strength relative to the neat polymer. However, very limited attention has been paid to the viscoelastic behavior of nanotubes reinforced polymer composites (NTRPC). Since the experimental techniques are so expensive, there is a need to develop analytical models that are capable of predicting the time-dependent viscoelastic behavior of such nanocomposites.

In this paper, the constitutive relation and linear viscoelastic behavior of NTRPC are studied using methods of micromechanics. First, the effects of volume fraction, shape, aspect ratio and orientation of carbon nanotubes (CNTs), on the overall elastic properties of NTRPC are obtained. Secondly, by incorporating the Dynamic Correspondence Principle (DCP), the elastic solution is extended to solve the related linear viscoelastic problem.

2 Geometric structure of SWCNTs

Carbon nanotubes are the fourth allotrope of condensed carbon. Two varieties of these tubes have been distinguished, the single walled carbon nanotubes (SWCNTs) and the multi-walled carbon nanotube (MWCNTs). The SWCNTs are generated by rolling up a Graphene sheet into a seamless cylinder with a constant radius. The atomic structure of nanotubes depends on tube chirality, which is defined by the Chiral vector C_h and the Chiral angle θ as shown in Fig 1. The Chiral vector and Chiral angle can be defined in terms of the lattice translation indices (n, m) and the basic vectors a_1 and a_2 of the hexagonal lattice as follows:

$$C_h = na_1 + ma_2 \quad (1)$$

$$\theta = \sin^{-1}\left[\frac{\sqrt{3}m}{2\left(\sqrt{m^2+mn+n^2}\right)}\right] \quad (2)$$

Using this (n, m) naming scheme, the three types of orientation of the carbon atoms around the nanotube circumference are specified as Armchair, Zigzag, or Chiral. The chirality of nanotubes has significant impact on its transport properties, particularly the electronic properties [3].

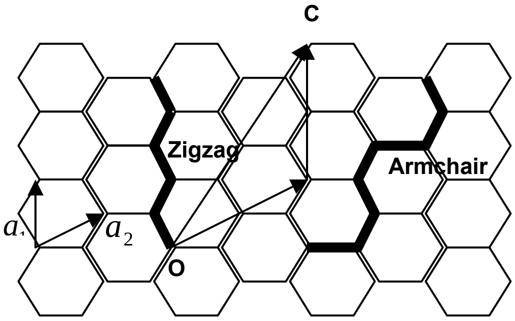

Fig. 1 Schematic of the hexagonal lattice of Graphene sheet

3 MICROMECHANICAL ANALYSIS

The first research on viscoelastic behaviour of composites is return to the works of Hashin [4] and Schapery [5]. After that, many researches oriented toward the investigation of the effects of fibre orientation [6] and intermediate phase [7] on the mechanical properties of composites. In the following we are going to derive the constitute relation for viscoelastic behaviour of nanocomposites reinforced with CNTs. To achieve this goal we have considered the following assumptions:

- The CNTs are straight and the effects of waviness are ignored
- We consider two cases:
  - (a) Random dispersion of NTs which leads to isotropic behaviour and
  - (b) Uniform dispersion of NTs which leads to transverse isotropic behaviour of nanocomposites
    - The interphase region (between NT and neat polymer) is modelled as the elastic and transverse isotropic material which the mechanical properties are determined through the Equivalent Continuum Modelling (ECM) technique [8].
    - The overall behaviour of nanocomposites is modelled as linear viscoelastic
    - The mechanical properties of NTs and polymer are independent of temperature
    - The micromechanical model is based on the Mori -Tanaka approach [9]

The stress-strain relation for linear viscoelastic material is defined as [10]

$$\sigma(t)=\int_0^t L(t-\tau)\dot{\varepsilon}(\tau)d\tau, \quad \varepsilon(t)=\int_0^t M(t-\tau)\dot{\sigma}(\tau)d\tau$$

(3)

where the dot denotes the differentiation with respect to time (t), and L(t) and M(t) are the stress relaxation stiffness and creep compliance tensors, respectively.

By applying the Laplace-Carson transformation as:

$$\hat{f}(s)=s\int_0^\infty e^{-s\tau} f(\tau)d\tau$$

(4)

to Eq. (3) gives

$$\hat{\sigma}(s)=\hat{L}(s)\hat{\varepsilon}(s), \qquad \hat{\varepsilon}(s)=\hat{M}(s)\hat{\sigma}(s)$$

(5)

where the hat indicates the transformed function in the Carson domain, and s is the transform variable. In fact, according to the Correspondence Principle in viscoelasticity (e.g., [11–13]), if a Laplace transformable, analytical solution exists for a problem in linear elasticity, the solution for the corresponding problem in linear viscoelasticity in the Carson (transformed) domain can be directly obtained from the former by replacing stiffness and compliance tensors with its viscoelastic counterpart $\hat{L}(s)$ or $\hat{M}(s)$, respectively. In particular, for a transversely isotropic composite containing unidirectionally aligned, identical CNTs the Eq. (5) is written as:

$$\begin{cases}\hat{\sigma}_{11}=\hat{L}_{11}\hat{\varepsilon}_{11}+\hat{L}_{12}\hat{\varepsilon}_{22}+\hat{L}_{12}\hat{\varepsilon}_{33},\\ \hat{\sigma}_{22}=\hat{L}_{12}\hat{\varepsilon}_{11}+\hat{L}_{22}\hat{\varepsilon}_{22}+\hat{L}_{23}\hat{\varepsilon}_{33},\\ \hat{\sigma}_{33}=\hat{L}_{12}\hat{\varepsilon}_{11}+\hat{L}_{23}\hat{\varepsilon}_{22}+\hat{L}_{22}\hat{\varepsilon}_{33},\\ \hat{\sigma}_{12}=2\hat{L}_{44}\hat{\varepsilon}_{12},\\ \hat{\sigma}_{23}=2\hat{L}_{66}\hat{\varepsilon}_{23}=\left(\hat{L}_{22}-\hat{L}_{23}\right)\hat{\varepsilon}_{23},\\ \hat{\sigma}_{31}=2\hat{L}_{44}\hat{\varepsilon}_{31},\end{cases}$$

(6)

Where L_{ij} are the components of the stiffness tensor. Therefore the normal and transverse Young's modulus, shear modulus and in plane and out of plane Poisson's ration can be determined as:

$$\begin{cases} \hat{E}_{11} = \hat{L}_{11} - \dfrac{2\left(\hat{L}_{12}\right)^2}{\hat{L}_{22} + \hat{L}_{23}}, \\ \hat{E}_{22} = \hat{L}_{22} + \dfrac{\left(\hat{L}_{12}\right)^2\left(\hat{L}_{23} - \hat{L}_{22}\right) + \hat{L}_{23}\left[\left(\hat{L}_{12}\right)^2 - \hat{L}_{11}\hat{L}_{23}\right]}{\hat{L}_{11}\hat{L}_{22} - \left(\hat{L}_{12}\right)^2}, \\ \hat{G}_{12} = \hat{L}_{44}, \quad \hat{\upsilon}_{12} = \dfrac{\left(\hat{L}_{12}\right)}{\hat{L}_{22} + \hat{L}_{23}}, \quad \hat{\upsilon}_{23} = \dfrac{\left[\hat{L}_{11}\hat{L}_{23} - \left(\hat{L}_{12}\right)^2\right]}{\hat{L}_{11}\hat{L}_{22} - \left(\hat{L}_{12}\right)^2}, \end{cases} \tag{7}$$

For isotropic composites containing randomly oriented NTs, the above five independent constants are reduced to only two independent constants.

4 NuMERICAL RESULTS

In this section the effects of aspect ratio and volume fraction for isotropic and transversely isotropic composite are investigated.

a. Isotropic behaviour

In the case of randomly oriented NTs, the overall behaviour of composite will be isotropic.

In Fig. 2 the effect of aspect ratio (ratio of the length to diameter of NTs) on the axial creep compliance (inverse of Young's modulus) is shown. As it is seen with increasing the aspect ratio, the creep compliance of composite is reduced.

In Fig. 3 the effect of volume fraction on the shear creep compliance (the inverse of shear modulus) is shown. By increasing the volume fraction, the shear creep compliance is decreased. By comparing the Fig. 2 and 3, we can see that the effect of aspect ratio is higher than volume fraction.

It should be mentioned that with passing the time the shear and axial creep compliance are increased.

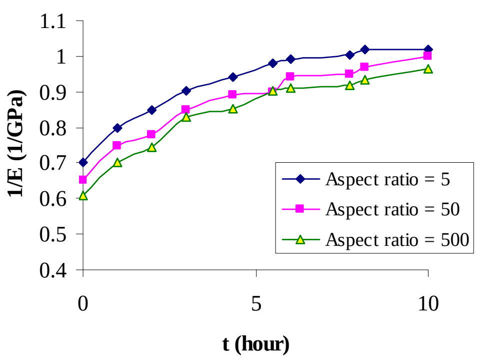

Fig. 2 variation of axial creep compliance with time for different values of aspect ratio

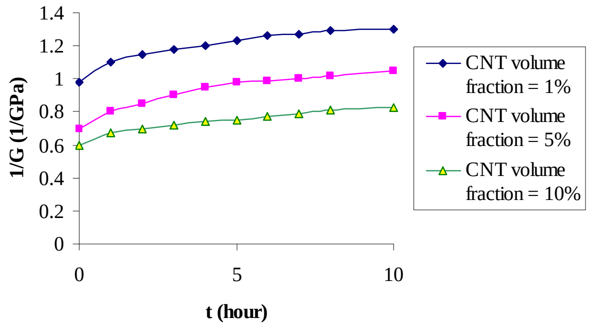

Fig. 3 variation of shear creep compliance with time for different values of volume fraction

b. Transverse isotropic behaviour

In the case of uniformly distributed NTs, the overall behaviour of composite will be transversely isotropic with five independent material constants.

In Fig. 4 the effect of aspect ratio on the axial creep compliance M11 and axial shear creep compliance M44 is shown. As it is seen with increasing the aspect ratio, the creep compliance of composite is reduced. Of course the effect of aspect ratio on M11 is clearly higher than M44.

In Fig. 5 the effect of aspect ratio on the transverse creep compliance (M22) and the plane strain bulk modulus (k23) is shown. With increasing the aspect ratio, the transverse creep compliance is decreased. However aspect ration has almost no effect on the plane strain bulk modulus

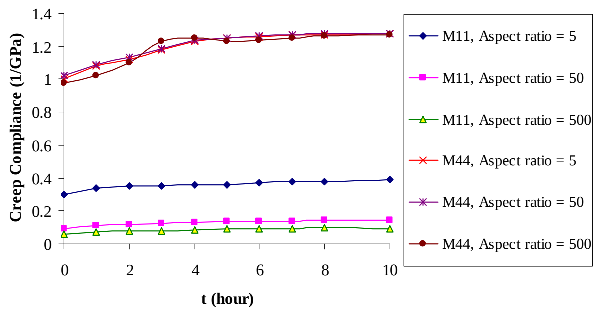

Fig. 4 variation of axial and shear creep compliance with time for different values of aspect ratio

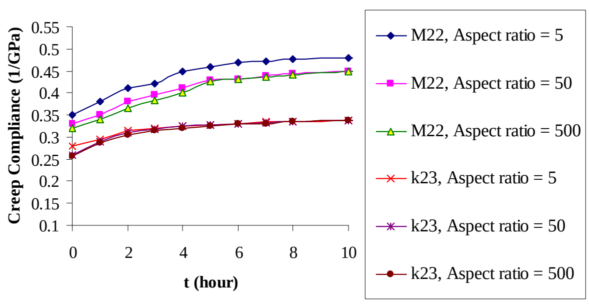

Fig. 5 variation of transverse creep compliance and the plane strain bulk modulus with time for different values of aspect ratio

In Fig. 6 and 7 the effect of volume fraction on the axial creep compliance (M11), the axial shear creep compliance (M44), transverse creep compliance (M22) and the plane strain bulk modulus (k23) are shown. With increasing the volume fraction, M11 and M44 are decreased; however k23 and M22 are almost constant. These trends are in good agreement with previous results [14, 15]. Furthermore, with 0% and 100% volume fraction of NTs we get the mechanical properties of neat polymer and NTs respectively.

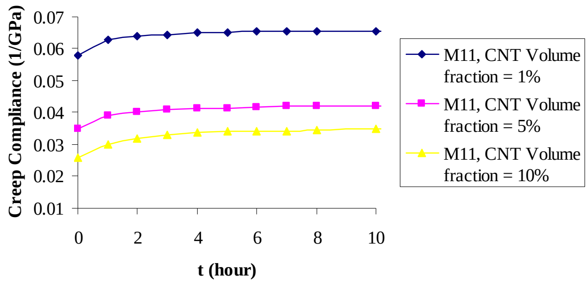

Fig. 6 variation of the axial creep compliance with time for different values of volume fraction

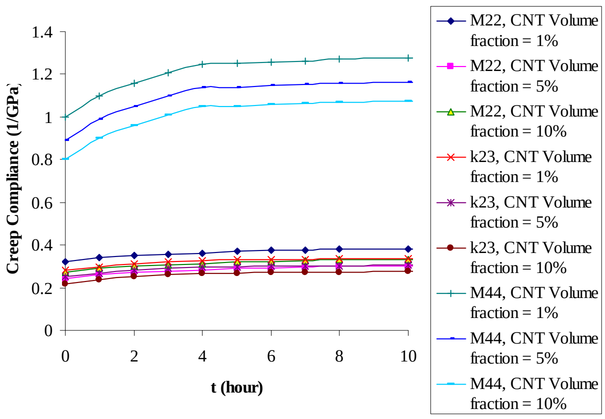

Fig. 7 variation of transverse creep compliance, axial shear creep compliance and the plane strain bulk modulus with time for different values of volume fraction

5 CONCLUSIONS

Based on the Dynamic Correspondence Principle (DCP) and the method of micromechanics, the effect of volume fraction, aspect ratio and orientation of NTs on the viscoelastic behaviour of polymer composites reinforced with NTs are obtained. The computational results have lead to the following conclusions:

- For randomly oriented NTs,

6 By increasing volume fraction or aspect ratio the M44 and M11 are decreased.

7 The effect of volume fraction is higher than aspect ratio

- For uniformly distributed NTs

(a) The effect of aspect ratio on M44 and k23 is insignificant but has a great effect on M11.

(b) By increasing the aspect ratio, the axial stiffness of the composite is improved

(c) By increasing of the volume fraction M11 is decreased however other mechanical properties are almost constant.

Investigation the effects of agglomeration and waviness of NTs and the variation of temperature on the viscoelastic properties on nanocomposites, can be studied in future.

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The direct incorporation of micro-encapsulated Phase Change Materials in the concrete mixing process – A feasibility study

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Abstract

The present study refers to a set of tests using different amounts of micro-encapsulated PCM directly mixed into self-compacting concrete. This SCC is investigated regarding its fresh and hardened properties. It will be shown that increasing PCM amounts lead to lower thermal conductivity and increased heat capacity, which both significantly improve the thermal performance of concrete structures. On the other hand, a significant loss in strength and a micro-structural analysis both indicate that a large part of the capsules cannot withstand the mixing process, which is a result of insufficient mechanical and chemical resilience of the encapsulating material.

Keywords:
PCM, self-compacting concrete, latent heat capacity, hydration heat

1 INTRODUCTION

Phase Change Materials have the ability to absorb and to release thermal energy at a specific temperature when their state changes. The heat capacity and high density of concrete combined with the use of the latent heat storage of PCM can provide new energy saving concepts, for example in combination with solar energy. In fresh concrete mixes PCM could be added to prevent high hydration temperature peaks, which can result in higher compressive strength and better durability.

The use of PCM in building materials and components has been researched for multiple years and different materials and components have been regarded to incorporate them (e.g. [1] and [2]).

Because the direct use of a micro-encapsulated mixture of paraffins in fresh concrete has not received much attention yet, a mixture of paraffins will be used in this research. It concerns a commercially available product for the building industry with a melting point of 23 °C named Micronal DS 5008 X. According to the product descriptions, it is described as a mixture of paraffin waxes in powder form, encapsulated in polymethyl methacrylate microcapsules. The technique of micro-encapsulation is used here in order to surround the liquid/solid paraffin phase with a hard shell. This way the liquid paraffin (< 23 °C) is transformed into a powder and prevented from entering the surrounding matrix. Due to the encapsulation, it should be theoretically possible to disperse the paraffin in the fresh concrete mix and to melt it without any interaction between the PCM and the concrete constituents.

This research aims to contribute to existing knowledge on the use of micro-encapsulated PCM in self-compacting concrete (SCC) by conducting experiments regarding its behavior during mixing, hydration and after hardening. The properties of three recipes containing 1% PCM, 3% PCM and 5% PCM (by mass of concrete) were compared with one reference mix. These additions correspond to 2.5 – 12.4% of volume in the mix. The properties of fresh SCC were evaluated using the J-ring test and V-funnel test. During hydration the influence of PCM on the heat development was firstly modeled and secondly monitored in situ. Finally, the hardened concrete was subjected to compressive strength tests and tests to measure its thermal properties. Furthermore, densities were measured and visual observations were reported. Moreover, the micro-structure has been analyzed by using SEM.

2 CHOICE OF COMPONENTS – MIX DESIGN

A practical aim of this research is to prevent high hydration temperature peaks during the first day of hydration. Therefore, a deliberately high cement dosage of 450 kg/m^3 was selected. In order to increase the hydration heat development even more a mixture of cement with high fineness (micro-cement) as well as a R type cement with higher clinker content was selected.

In order to account for the varying PCM amounts in the mixes, a non reactive material with comparable particle size distribution is necessary to substitute the respective PCM volume. This way it is assured that all mixes are comparable from the granulometric point of view. Accordingly, all respective variations compared to the (PCM-free) reference mix can be assigned to the influence of the PCM. For this test a dolomitic marble powder is selected, which in former research was successfully applied in SCC production [3]. PCM and marble powder were substituted on volumetric base and are of similar particle size distribution. The 5% mix is an exception since the PCM volume in this case is higher than the available marble volume. Therefore, a slightly higher fines content is present in this mix.

Moreover, the concrete is designed with common aggregates such as fine sand 0-1, 0-4 sand, an intermediate gravel fraction 2-8 and a gravel fraction 4-16. All sand and gravel fractions are river aggregates and therefore show smooth and round shape. Finally, a third generation superplasticizer of the polycarboxylate ether (PCE) type was used to adapt the workability and to adjust the mixes to about the same slump-flow class.

The above described materials have been used to design self-compacting mixes with increasing amounts of PCM. Besides one reference mix without PCM three more mixes were designed containing 1%, 3% and 5% of PCM materials based on their total mass. The applied design method is similar to the SCC mix design of [3]. The method basically focuses on the optimization of the solid granular skeleton. Figure 16 presents the entire particle size distribution of the reference mix including the target grading and all individual materials, based on the design method elaborated in [4]. The micro-encapsulated PCM material is considered as a particle and therefore part of the optimization.

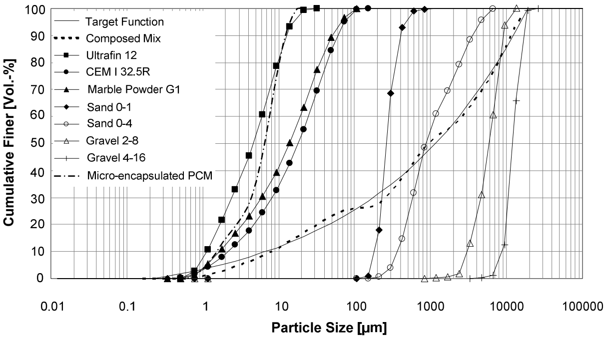


Figure 16: Plot of the total grading of the PCM reference mix, showing target grading compared to the achieved grading as well as all individual constituents. The PCM capsules are not constituent of the reference mix.

3 EXPERIMENTAL PROCEDURE

3.1 Differential scanning calorimetry

For this test series a micro-encapsulated PCM was obtained which is a paraffin wax encased in polymethyl methacrylate microcapsules. A small sample of these microcapsules has been used for the differential scanning calorimetry (DSC) experiment, deploying a Differential Thermal Analyzer (DTA) Perkin Elmer DSC7. For the given temperature range from -20 °C – 50 °C a cyclic heating/cooling/heating scan was conducted at a heat-ing/cooling rate of 10 °C/min with 2 min isothermal holds at both minimum and maximum temperatures. Based on this, during solidification (cooling) an enthalpy δH_{exoth} of 102.8 J/g in a temperature range of 22.1 – 9.3 °C was measured. For the melting (heating) the enthalpy δH_{endoth} amounts to 99.7 J/g in a temperature range of 18.8 – 35.4 °C. The authors are aware of, that higher values of heating or cooling rate lead to broader melting ranges and vice versa [5]. Figure 17 provides the heating and cooling scans. The selected heating/cooling rate is responsible for the observed super-cooling effect shown in Figure 17. This behavior is normally not to be expected when a lower heating/cooling rate of 0.1 – 0.5 °C/min is applied. Nevertheless, the heating/cooling rate does not influence the total melting/freezing enthalpy.

3.2 Concrete mixing

The mixing of the self-compacting PCM mixes took place in four steps. At first all solids except for the PCM are mixed for 30 seconds in order to homogenize the dry components. Thereafter, about 90% of the total water dosage is added and mixing is continued for further two minutes. In this range of time the superplasticizer is added directly after the water in order to assure sufficient mixing time for the plasticizer to be homogeneously dispersed and activated. At this latest possible moment the micro-encapsulated PCM is added to the mixing process in order to expose it as short as possible to the mixing process. After the PCM addition, part of the remaining SP and water is dosed to, again, obtain the desired self-compacting characteristics. This is for the time being controlled by visual inspection. A subsequent slump-flow and V-funnel test decides if an additional water or SP dosage is necessary to obtain equal workability in terms of relative viscosity and yield stress. All four mixes succeeded in achieving similar workability with only one additional dosage step. Table 2 refers to the final water and SP dosages used for the respective mixes.

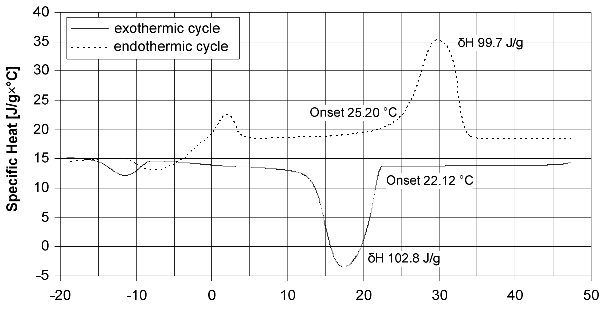


Figure 17: Plot of specific heat as a function of temperature for the heating and cooling cycles of the applied PCM.

	Reference mix	1% mix	3% mix	5% mix

	Mass (kg)	Mass (kg)	Mass (kg)	Mass (kg)
Ultrafin 12	149.9	149.9	149.9	149.9
CEM I 32.5 R	299.7	299.7	299.7	299.7
Marble powder	170.2	98.0	0.0	0.0
PCM	0.0	23.3	70.0	113.7
Sand 0-1	139.6	139.6	139.6	139.6
Sand 0-4	655.3	655.3	655.3	655.3
Gravel 2-8	387.1	387.1	387.1	387.1
Gravel 4-16	319.6	319.6	319.6	319.6
SP - PCE Glenium 51	3.1	3.1	2.4	2.9
Water	203.2	207.4	211.5	248.4

Table 2: Mix composition.

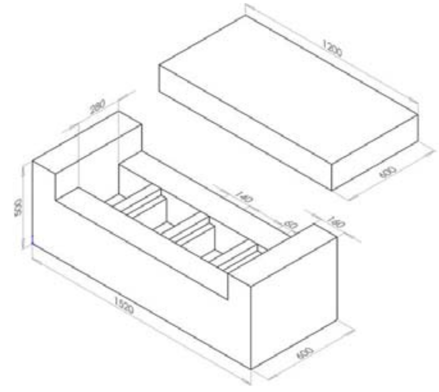


Figure 18: Depiction of the semi-adiabatic environment for four standard sized molds.

3.3 Semi-adiabatic curing

To measure the influence of PCM content on the peak temperature during hydration, an experimental setup has been constructed. A layer of cellular glass, 160 mm thick with a heat resistance of 3.81 m^2K/W, forms a semi-adiabatic environment for four standard cubic molds with an edge length of 150 mm according to EN 12390-1. The box-shaped environment measures 1520 × 600 × 500 mm^3 (l×w×h). The four molds were individually separated by three fixed septa of 50 mm cellular glass (see Figure 18). Around and within the molds thermocouples (type T) were placed to measures the temperature during the early stage of hydration. Data acquisition took place by using National Instruments USB-6215 and PICOs TC-08 in combination with a personal computer to store the data. The basis of this setup is comparable to setups used before [6], [7].

3.4 Thermal conductivity measurements

A “CT-METRE” was used for the conductivity measurements. The device uses the transient hot wire method conforming to ISO 8894-1:1987, DIN 51046 and ASTM D2326. The operating principle is based on the association of a heating device with a temperature sensor (both connected inside the same probe) intended to measure the temperature increase undergone by the sensor during a predetermined heating time. The method is not applicable when a phase change occurs in the material, as might be the case with the PCM containing mixes. To overcome the problem, the samples have been heated to 30 °C and the measurements have been performed at this temperature, which is well above the melting range of the PCM.

3.5 Specific heat capacity/thermal efficiency measurements

Unlike thermal conductivity, specific heat capacity (c_p) increases rapidly in the temperature range of phase change. This makes transient methods inappropriate for c_p measurements. The Differential Scanning Calorimetry method requires a representative sample of the material in the order of a few milligrams which is not possible with concrete samples consisting of particles up to 16 mm diameter. For the needs of inexpensive and reliable measurements an experimental setup (Figure 19) has been developed which allows measurements of heat capacity, thermal mass and thermal efficiency of building materials. The device applies variable thermal loads at the two sides of a flat-surface material sample, while measuring its thermal response. An extensive presentation of the concept and the corresponding operational principle can be found in [8].

Figure 19: Sample holder of the thermal mass measuring device (sample between two thermo-regulated plates).

4 RESULTS

4.1 Effects on the properties of fresh concrete

In order not to expose the PCM microcapsules to additional wear during pouring and compaction, a self-compacting mix was designed. These mixes start flowing at much lower yield stresses compared to plain concrete. Therefore, the concrete placing involves only a limited amount of shear stress for the microcapsules. Another reason for the choice of SCC is the faster heat development of SCC compared to standard plain concrete which is among others reported by [9].

The results on the fresh SCC properties are extensively discussed in [10]. Here, it can be summarized that all four mixtures resulted in good and partly excellent self-compacting properties. The increasing PCM dosage did not seem to influence any of these measures in a verifiable range. Only the visual inspection during the V-funnel and in particular the slump-flow experiments resulted in some uncommon observations. Here a white liquid was accumulated on top of the mixture in areas of slow flow or on resting concrete areas. This observation became especially obvious at the flow area behind the rods of the J-ring as well as along the circumferential line of the spreading concrete during slump-flow tests (cp. Figure 20). This behavior was only observed for the three mixes containing PCM and also became more prominent with increasing PCM content.

Figure 20: SCC after J-ring test with obvious flow marks behind the rods and around the spreading concrete.

4.2 Effects on the hydration temperature peak

The setup offers space to store four molds in an environment of 20 ±2 °C. After casting the temperature development of the four kernels was monitored for about 80 hours, taking measurements every minute. These results are shown in Figure 21.

The reference mix shows a peak temperature of 41 °C. This temperature is significantly lower than the results of [6] have shown for other Portland cement mixtures during hydration. The observed cooling refers to a leakage of heat. Otherwise, under totally adiabatic conditions, a temperature rise of about 76 °C to an absolute temperature of 98 °C would be expected, considering complete hydration of the cement. For very massive constructions, where adiabatic conditions can be assumed for the core volume, such a temperature rise would imply the boiling of the free water and cause fundamental durability problems.

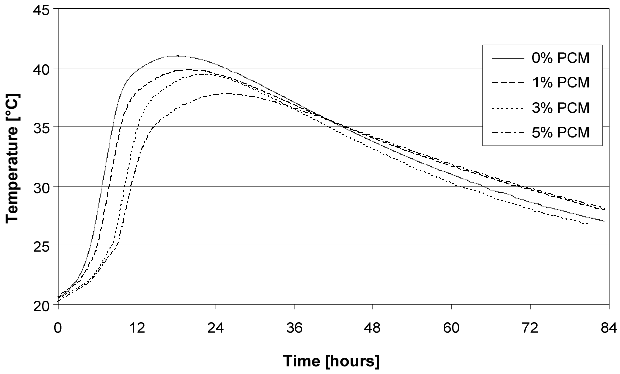


Figure 21: Temperature development of 4 self-compacting mixes in the kernel of the molds in a semi-adiabatic environment during the first 3.5 days after production.

Figure 21 shows that an increasing amount of PCMs results in a lower peak temperature. Because of the comparable availability of internal or chemical energy in all four mixes, more time is needed to come to the ambient temperature when the amount of PCMs is higher. The 3% and 5% PCM mixes show a small bow around 25 °C, being -according to the DSC experiment - the onset for the endothermic cycle.

Surprisingly, the 3% mix had a larger temperature rise than the 1% mix. In this case it could be that 1) the adiabatic surrounding did not suffice, that 2) more PCM particles were destroyed during mixing in the 3% mix than in the 1% mix, or that 3) the thermocouples were not able to register the temperature correctly. In future experiments these three aspects will be taken in consideration.

Regarding option number two, the analysis of the porosity using SEM showed that many PCM capsules were in fact destroyed. Nevertheless, the temperature registration showed that to a large extent, especially in the 5% mix, the peak temperature could be lowered. This could imply that, despite the partial destruction of the PCM capsules, a large part of the wax is still present in the concrete and could be potentially functioning.

4.3 Effects on mechanical properties

In order to evaluate the effect of PCMs on the mechanical properties of concrete, compressive strength measurements were executed. Therefore, five standard cubes per mixture with an edge length of 150 mm according to EN 12390-1 (2000) have been tested at the 28th day after production. The test procedure for compressive strength is conforming to EN 12390-3 (2001).

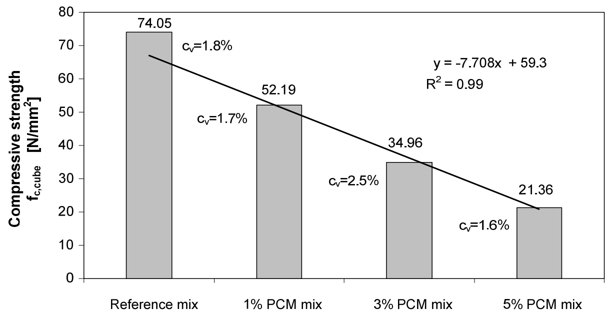


Figure 22: Compressive strength of the PCM mixes after 28 days [N/mm^2] including the coefficient of variation (c_v).

Since a new mix design, as described above, has been applied to this concrete, elevated strength compared to standard composition with equal cement content was expected. Therefore, a modification of Féret's equation was applied to get an indication for the possible compressive strength at 28 days [11]. This modification includes the contribution of other cementitious materials and reads as:

$$f_c = \frac{K_g R}{\left(1 + 3.1 \frac{W + A}{C\left(1 + K_1 + K_2\right) + BFS}\right)} \quad (1)$$

where K_g is an aggregate coefficient (typical values are 5.4 for crushed aggregates and 4.8 for rounded aggregate), R_c is the standard cement strength (cp. Table 3), W is the total effective water content, A is the volume of entrapped air and C is the weight of cement (in kg/m^3). The other variables, K_1, K_2 and *BFS*, refer to pozzolanic and latent hydraulic effects. Since none of these materials were used, these latter variables are zero. Including the relevant data in Eq. (3), the expected strength of the reference mix can be calculated to 46.2 N/mm^2. In fact a compressive strength of 74.1 N/mm^2 was determined. The significantly higher strength could for a large extent be attributed to the improved packing of the new mix design.

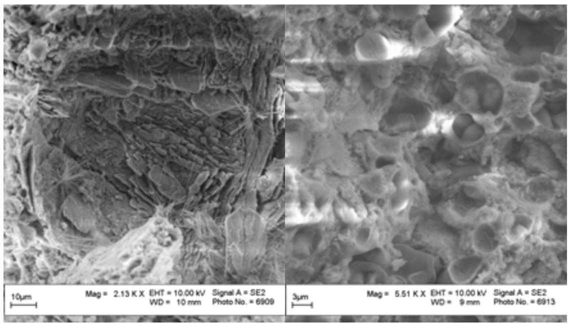
Cement type	Heat release after 1 day Q_{1day} [J/g]	Standard strength R_c [N/mm^2]
CEM I 32.5 R	139.3	57,3
Ultrafin 12	250.0	70.0

Table 3: Thermodynamic and strength properties of the deployed materials.

Results of the compressive strength measurement are presented in Figure 22. From the given data it can be clearly observed that increasing PCM dosages lead to significantly lower compressive strengths. From Figure 22 it can furthermore be concluded that the compressive strength of this specific mixture decreases by 13% for each additional percentage of PCM. This linear relation holds for the range of PCM contents considered.

4.4 Microstructural analysis

An analysis by means of scanning electron microscopy shows a porous microstructure and many, spherical voids which presumably contained PCM capsules before. As a mixture of paraffin probably also slightly varies in its melting temperature, softer paraffin melts earlier than the harder paraffin components. This causes a slight segregation during the melting process. Due to the immiscibility of the leaked paraffin with other concrete ingredients, solidification appears in the cavity of the matrix and at pore walls. An example is given with the SEM micrograph in Figure 23 (a). Here flaked structures of solidified wax cover the inner walls of the pore. Close to the pore walls it forms a type of cell wall which appears to be smooth from the outside (cp. left boundary). The surrounding structure is densely occupied with PCM capsules of the predominant size of about 6 µm (cp. Figure 23 right). These capsules appear to a large extent deformed and broken. These observations are very similar to those by Gschwander et al. [12], who found broken micro-capsules of the same type after pumping PCM slurries.



(a) (b)

Figure 23: SEM micrographs of (a) an open pore covered with solidified wax, and (b) a higher magnified (5.5k) part of the matrix with deformed and broken capsules, partly pure leaked wax is visible.

4.5 Effects on the thermal properties of hardened concrete

The study of the effects of PCM on the thermal properties of concrete includes measurements of thermal conductivity and specific heat capacity.

Thermal conductivity

In order to evaluate the effect of PCM on the thermal conductivity of concrete three mixes containing 1% PCM, 3% PCM and 5% PCM per weight, and a reference material were measured.

According to the standards, two samples of 100 × 100 × 50 mm^3 of every mixture were prepared for the measurements. Thermal conductivity measurements are presented in Figure 24. It is clearly indicated that the addition of PCM particles into the mass of the concrete results in a reduction of thermal conductivity. This can be explained by the enhanced air content and by the lower thermal conductivity of paraffin.

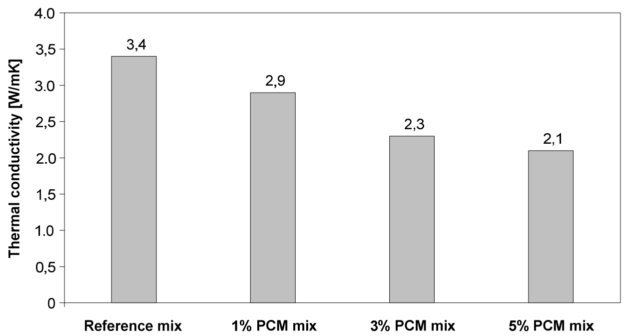


Figure 24: Thermal conductivity of the PCM mixes.

Specific heat capacity/thermal mass

For the specific heat capacity measurements four samples of the four different mixes were prepared at the appropriate dimensions, 200 × 200 × 30 mm^3 (l × w × h). The samples were introduced in the sample holder of the thermal analysis device at a temperature of 19 °C and were heated up to 28 °C. The temperature of the device during the heating process was maintained constant at 32 °C. The temperature of the samples and the heat flux from the device to the samples were recorded. Temperature and heat flux measurements allow the calculation of the heat capacity and thermal mass of the samples (Figure 25 and 11) as:

$$c_p = \frac{A\dot{q}}{m\left(\frac{dT}{dt}\right)} \quad (2)$$

$$M_{th} = m c_p \quad (3)$$

where c_p is the heat capacity of the sample, M_{th} the thermal mass, A the heat exchange area of the sample, q the heat flux per square meter, m the mass of the sample, T the temperature of the sample and t the time.

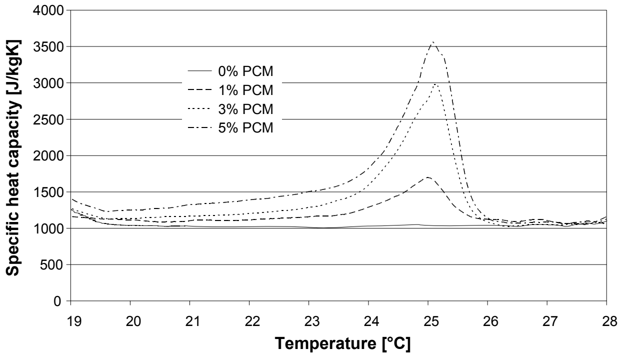


Figure 25: Specific heat capacity of the PCM mixes versus temperature.

Figure 25 and 11 present the measured specific heat capacity and thermal mass for the four samples versus temperature. In both Figures, the effect of increasing the percentage of PCM in the mixture is apparent in the melting temperature range of the PCM (23 °C – 26 °C). Comparison of Figure 25 and 13 indicates that, as expected, increasing the amount of PCM in the mixture increases significantly its specific heat capacity (up to 3.5 times for the 5% PCM content). However, there seems to be an upper limit to the increase of the thermal mass. The 5% PCM mixture has slightly more thermal mass than the 3% mixture inside the melting range of the PCM but less outside of this region. This can be the consequence of decreasing concrete density with increasing PCM content. As a result, a percentage more than ca. 5% (or 4%) of PCM in the mixture does not increase the thermal mass of the material.

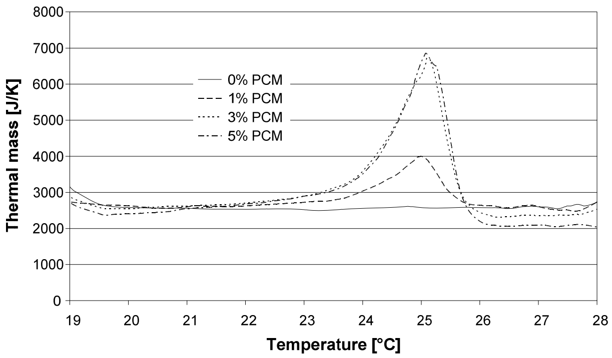


Figure 26: Thermal mass of PCM mixes vs. temperature.

4.6 Effect of PCM quantity on thermal performance

Evaluation of thermal performance of building materials used for building envelopes is generally performed by measuring the decrement factor and time lag. In the case of building materials containing PCM, the above two measures may not be representative since they do not take into account the large amount of heat contributions/subtractions in the temperature range that the phase change occurs [13]. An appropriate method of evaluating the effect of PCM on thermal efficiency of structural elements is the comparison of the heat flux at the indoor surface of a wall with different amounts of PCM [14].

In the current work the above described thermal analysis device is used to simulate indoor and outdoor temperatures and the corresponding temperature profiles are imposed at the two sides of the sample. The outdoor temperature is assumed to have a sinusoidal variation from 18.5 °C – 28.5 °C for 48 hours (for instance resembling temperature variations in a South European country), while the indoor temperature is set stable at a level of 23.5 °C. Temperatures and heat fluxes on both surfaces of the same samples as the ones used for the specific heat capacity measurements are recorded.

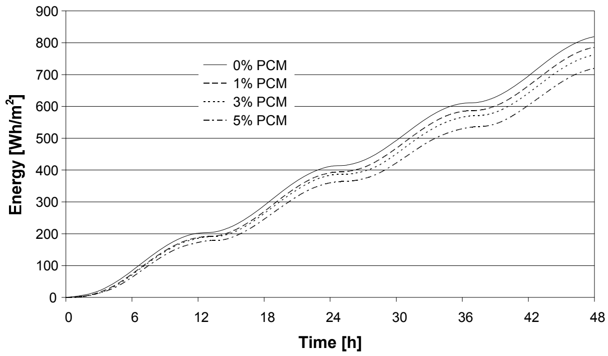


Figure 27: Energy required for maintaining indoor temperature stable at 23.5 °C.

Integration of the measured heat flux on the inner side of the sample provides a measure of the total heat losses towards the indoor environment (Figure 27). The heat flux measurements of demonstrate an up to 11% variation in the measured maximum and minimum peak values for the sample with 5% PCM content.

5 CONCLUSION

The mix design method presented in [3] for SCC containing marble powder was successfully adopted and applied to the three mixes containing micro-encapsulated PCM. Based on the J-ring and V-tunnel test, all four mixtures featured good self-compacting properties. Using the developed recipes the increasing PCM dosage did not seem to influence the properties of the fresh concrete.

The modeling and experiments involving hydration showed that the temperature peak of hydration could be reduced up to 28.1% by increasing the PCM content to 5%. However, the heating rate cannot be changed by the PCM, only the absolute temperature peak is lowered by the amount of energy temporarily stored in the PCM. The emission of heat from the sample will therefore continue for a longer time when the PCM content is higher.

Regarding the thermal properties of hardened self-compacting concrete with PCM, the experiments showed a reduction of thermal conductivity with increasing amounts of PCM.

The measurements have indicated that the overall behavor of each sample is the combined result of conductivity and specific heat variations. Moreover, with increasing PCM content the thermal mass of the sample increases significantly. Although the specific heat capacity increased with increasing amount of PCM in the considered temperature range (24 – 26 °C), the thermal mass seems to be bound by a maximum of approximately 6800 J/K at 4% to 5% PCM.

The increase in thermal mass could improve significantly the thermal performance of concrete in terms of energy saving. For example, savings up to 12% could be expected as a result of the inclusion of 5% PCM in the mix.

More experiments with samples incorporating dedicated amounts of PCM above chosen percentages could provide better insight into the exact value of this maximum. In practice, both the lower thermal conductivity and the increased heat capacity significantly improve the thermal performance of concrete and could lead to energy savings in building applications.

Although the loss of compressive strength is significant, concrete with PCM content up to 3% and an accompanying compressive strength of 35 N/mm^2 is still for most constructional purposes well acceptable. The loss of compressive strength can be assigned to destructed shells of the PCM capsules for reasons mentioned in paragraph 4.4. Observations made during a side experiment show that the respective micro-encapsulated PCM material is not suitable for the requirements of a concrete application [10]. The released wax from the microcapsules interferes into the surrounding concrete matrix and hinders a sufficient strength development in multiple ways. Here, the possible inhibition of the water transport and hence an interruption of the hydration, and the possible development of phase interfaces by the wax are to be mentioned. Therefore, the main recommendation to be given involves the development of stronger shells for microencapsulated PCM. These stronger shells have to withstand the highly alkaline conditions, which in addition to the mechanical impact have a negative influence on the strength of the shells.

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